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CONTENTS

PAGES

Beryl-tantalite pegmatites of Northeastern Brazil.
By W. D. Johnston, Jr. 1015-1070

Eustatic shore lines in the Pacific. By H. T. Stearns 1071-1078

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Preglacial History of Bermuda. By H. B. and D. M. Moore

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BERYL-TANTALITE PEGMATITES OF NORTHEASTERN BRAZIL

BY W. D. JOHNSTON, JR.

CONTENTS

	Page
Abstract	1017
Introduction	1017
Acknowledgments	1018
Geography	1019
Geology	1019
General features	1019
Seridó schist	1023
Granites	1023
Younger sandstones	1023
Diabase dikes	1024
Physiographic history	1024
Pegmatites	1024
Classification	1024
Form and size	1025
Relation to regional structure	1027
Internal zoning	1028
Mineralogy	1030
Essential minerals	1030
Accessory minerals	1032
Origin	1040
Production	1042
Mining methods	1042
Descriptions of individual pegmatites	1042
Picuí-Parelhas area of Paraíba and Rio Grande do Norte	1042
General considerations	1042
Algodão	1043
Boqueirão	1043
Damião	1043
Dinheiro	1044
Feio	1045
Forte	1046
Gamenho	1047
Garrote	1047
Malhada Grande	1048
Mamões	1049
Marimbondo	1050
Pedra Branca	1052
Piaba Nº1	1053
Quixabeira	1054
Redondo	1055
Santo Antonio	1055
Seridózinho	1055
Tabôa	1055

Tanquinhos 1055
Tibiri 1060
Urubú 1060
Quixeramobim-Cachoeira area, Ceará 1060
General Considerations 1060
Belém 1060
Belo Horizonte Nº 2 1061
Bom Jesus de Francisco Carneiro Machado 1061
Grossos Nº 2 1061
Lapinha 1062
Logradouro 1062
Olho d'Agua 1062
Poço dos Cavalos 1063
Soledade 1064
Várzea Torta 1064
Other mines in the Quixeramobim-Cachoeira area 1064
Cascavel-Cristais area, Ceará 1065
General Considerations 1065
Angicos 1066
Bangue 1066
Joazeiro 1066
Jatobá 1066
Jucas Nº 1 1066
Jucas Nº 2 1066
Lago do Brito 1067
Mulungú 1067
Parelhas 1067
Serrinha Nº 1 1067
Serrinha Nº 2 1068
References cited 1068

ILLUSTRATIONS

Figure Page
1. Index map of Northeastern Brazil 1020
2. Index map of Paraíba and Rio Grande do Norte 1021
3. Index map of the Quixeramobim-Cachoeira area, Ceará 1022
4. Index map of the Cascavel-Cristais area, Ceará 1022
5. Plan diagram of the Paraíba and Rio Grande do Norte pegmatites 1026
6. Plan diagram of the Ceará pegmatites 1027
7. Generalized sketch of a heterogeneous pegmatite 1028
8. Sketch section of a small heterogeneous pegmatite 1029
9. Sketch section across west half of Tabôa, Parelhas, Rio Grande do Norte 1030
10. Sketch sections of the Boqueirão mine, Parelhas, Rio Grande do Norte 1031
11. Sketch section of Alto Feio, Piciú, Paraíba 1032
12. Drawings of three beryl crystals from Alto Cruzeiro, Picuí, Paraíba 1033
13. Diagrammatic sketch of Morada Nova mine, Parelhas, Rio Grande do Norte 1034
14. Sketch of an underground face on the west side on Tanquinhos, Picuí, Paraíba 1035
15. Sketch map of the vicinity of São Tomé, Rio Grande do Norte 1037
16. Sketch of a face at Poço dos Cavalos, Quixeramobim, Ceará 1039
17. Paragenetic diagram 1041
18. Sketch map of Boqueirão, Parelhas, Rio Grande do Norte 1044
19. Sketch map of Damião, Picuí, Paraíba 1045
20. Sketch section of Damião, Picuí, Paraíba 1045
21. Sketch map of Feio, Picuí, Paraíba 1046

22. Sketch section of Feio, Picuí, Paraíba 1047
23. Sketch sections across the southeast half of Feio, Picuí, Paraíba 1047
24. Sketch map of Forte, Picuí, Paraíba 1048
25. Sketch map of Malhada Grande, Parelhas, Rio Grande do Norte 1049
26. Sketch of a face of the east tunnel, Malhada Grande, Parelhas, Rio Grande do Norte 1050
27. Sketch map of Mamões, Parelhas, Rio Grande do Norte 1051
28. Sketch map of Pedra Branca, Acarí, Rio Grande do Norte 1052
29. Sketch map of Piaba No. 1, Picuí, Paraíba 1053
30. Sketch map of the Quixabeira area, Picuí, Paraíba 1054
31. Sketch map of Seridōzinho, Joazeiro, Paraíba 1056
32. Sketch map of the Tabôa area, Acarí, Rio Grande do Norte 1057
33. Sketch map of Tanquinhos, Picuí, Paraíba 1058
34. Sketch section at Tanquinhos, Picuí Paraíba 1059
35. Sketch map of Poço dos Cavalos, Cachoeira, Ceará 1063
36. Sketch map of Várzea Torta, Cachoeira, Ceará 1065

Plate — Facing page

1. Homogeneous and heterogeneous pegmatites 1024
2. Heterogeneous pegmatites 1025
3. Mineralogic detail of heterogeneous pegmatites 1030
4. Mineralogic detail of heterogeneous pegmatites 1031
5. Recovery of tantalite 1042

ABSTRACT

Microcline-muscovite-quartz pegmatites in Northeastern Brazil have yielded approximately 600 metric tons of tantalite and 8000 metric tons of beryl, between 1937 and 1944. Other economic minerals are cassiterite, muscovite, amblygonite, and spodumene.

The regional rocks are pre-Cambrian schists and quartzites intruded by granites.

The pegmatites range from homogeneous textures without notable internal differentiation to heterogeneous textures with pronounced internal zoning. In the latter type, the essential minerals—microcline, muscovite, and quartz—form gigantic crystals, and the accessory minerals—tantalite, beryl, spodumene, and amblygonite—crystallize on a comparable scale.

Aside from late albitization of the microcline, there appears to be little evidence that the differentiation in the heterogeneous pegmatites resulted from a series of complex replacements. The field evidence appears, rather, to indicate deposition in a single cycle with a progressive increase in crystal size from walls to center.

Forty-two characteristic heterogeneous pegmatites are described, and plane-table sketch maps for some of them are reproduced.

INTRODUCTION

The pegmatites of Northeastern Brazil are one of the world's most important sources of tantalite and beryl. From the start of mining in 1937 until the end of June 1944 they have yielded approximately 600 metric tons of tantalite and 8000 metric tons of beryl. Smaller amounts of cassiterite, muscovite, spodumene, and amblygonite have also been obtained from them.

Most of this production came from the Picuí-Parelhas area in the states of Paraíba and Rio Grande do Norte. Recently, a smaller amount of these minerals has been obtained near Berilândia, southeast of Quixeramobim, in the central part of the neighboring state of Ceará.

This report is based upon four visits to the pegmatite area. My first visit, June and July 1942, was to appraise the production possibilities of beryl and tantalite of Paraíba and Rio Grande do Norte; my second visit in July and August 1943 primarily was to appraise the production possibilities of scheelite in the same region but gave the opportunity to visit many of the beryl-tantalite pegmatites; my third visit was in January, February, and March 1944, when I mapped some of the pegmatites of Paraíba and Rio Grande do Norte; and my fourth visit was in September 1944, when I mapped some of the pegmatites in Ceará.

Two reports (Johnston, 1945a; 1945b) on these pegmatite areas have been published, in Portuguese, by the Departamento Nacional da Produção Mineral. The purpose of this paper is to make available, in English, a description of the pegmatites of Northeastern Brazil.

Moraes (1938) and Souza (1939) were the first to write about the tantalite and beryl deposits of the Northeast. Later, Almeida (1941) and others (Almeida, Johnston, Scorza, and Leonardos, 1943; 1944; Scorza, 1944; Rolff, 1943; 1944a; 1944b; 1944c; 1944d; Catriú, 1944; Pough, 1945a, 1945b) described some of the deposits in greater detail. Recent work by Rolff (1945), which I was privileged to read in manuscript form, soon will be published by the Divisão de Fomento da Produção Mineral.

Several papers about the scheelite deposits of Paraíba and Rio Grande do Norte, which were discovered in 1942, have also been published (Leonardos, 1943; Rabello, 1943; Johnston and Vasconcellos, 1943; 1945; Johnston, 1944a).

ACKNOWLEDGMENTS

To my good friends in the Departamento Nacional da Produção Mineral, I am indebted for much help and many courtesies, both in the field and in Rio de Janeiro. My first visit was made at the invitation of Dr. Glycon de Paiva in the company of Dr. Sandoval Carneiro de Almeida, then Chief of the Campina Grande office of the Divisão de Fomento da Produção Mineral, Dr. Evaristo Penna Scorza, petrographer of the Divisão de Geologia e Mineralogia, and Professor Othon H. Leonardos of the University of Brazil. Professor Leonardos again joined me in the field in 1944. Dr. Onofre Chaves, Dr. Domingos Martins Fleury da Rocha, Dr. Mario Pinto, Dr. Alexandre Girotto, and others have been helpful in many ways. During two trips I had the pleasure of spending several days in the field with Dr. Paulo Anibal Marques de Almeida Rolff who has been studying the pegmatites of the area since late 1942. His generosity in furnishing mineral specimens and in making his observations available to me is greatly appreciated.

The members of the U. S. Purchasing Commission stationed in the Northeast have been generous with their help. I am especially indebted to Messrs. James Moore, W. E. Fourqurean, Ray Worley, and E. H. Page.

Silveira Dantas, of the firm of Silveira Brasil & Cia, of Campina Grande, was responsible for my early education in the mineral tantalite. In his warehouse it was possible to examine several tons of that rare mineral at any time. Florêncio Luciano and Antonio José de Lima, of Parelhas, have aided me in many ways.

In Ceará, José C. Saboia and Adalberto Benevides de Magalhães furnished much information of value.

Alexandre Leite de Barros served efficiently as my field assistant in mapping the pegmatites in 1944. To him I am indebted for both help and companionship.

José Francisco Lauria, Senior Draftsman in the Rio de Janeiro office of the U. S. Purchasing Commission, made all the drawings in this report.

The photographs on Plate 5 were made by Alan Fisher, of the office of the Co-ordinator of Inter-American Affairs, and are here reproduced with permission of that office.

GEOGRAPHY

Figure 1 is an index map of Northeastern Brazil showing the three principal pegmatite areas. Figures 2, 3, and 4 show the location of individual pegmatites in each area. Pegmatites described in the text are indicated by a heavier symbol and named on the maps.

In the Picuí-Parelhas area (Fig. 2) the precise location of the boundary between the states of Paraíba and Rio Grande do Norte is questionable, as maps of municipalities of the two states do not coincide. Consequently, the interstate boundary shown in Figure 2 is a compromise, and it is uncertain whether certain pegmatites near the boundary actually are in Paraíba or Rio Grande do Norte. From a geological viewpoint, however, such political considerations are of small consequence.

Campina Grande in Paraíba, at the terminal of the railroad to Recife, João Pessoa, and Natal, is the commercial center of the tantalite-beryl industry. It is connected with Patos, Parelhas, Acarí, Currais Novos, Angicos, Natal, and Fortaleza by an excellent gravel road built and maintained by the Inspetoria Federal de Obras Contra as Sêcas. Picuí is reached by secondary roads from Soledade, Carnaúba, and Currais Novos. Most of the pegmatites now being mined have passable roads. that can be traveled by either automobile or jeep.

Most of the productive pegmatites lie within the area defined by a line extending from Equador to Parelhas, Carnaúba, Frei Martinho, Picuí, Pedra Lavrada, Joazeiro, and Equador. Other producing pegmatites occur in the São Tomé-Lages area and in the municipality of Santa Luzia.

The Quixeramobim-Cachoeira area (Fig. 3) is most readily accessible by automobile from Jaguaribe, on the central highway of the Inspetoria Federal de Obras Contra as Sêcas. A poorer road roughly parallels the railroad from Quixeramobim to Fortaleza. Most of the mines described in that area can be reached by automobile, and all of them by jeep.

The Cascavel-Cristais area (Fig. 4) is traversed by the central highway, and all the pegmatites described are connected with that highway by automobile roads.

GEOLOGY

GENERAL FEATURES

The rocks of the Picuí-Parelhas region are principally pre-Cambrian gneisses and mica schists intruded by granites and cut by pegmatites and quartz veins. Subsequent erosion reduced the area to a peneplane upon which Cretaceous or younger sandstones were deposited. The present cycle of erosion has partially destroyed the old peneplane and has bared batholithic granite masses by stripping away the softer

schist. Because the pegmatites generally are more resistant to erosion than is the schist, they commonly stand in relief as conspicuous topographic features, locally known as "altos".

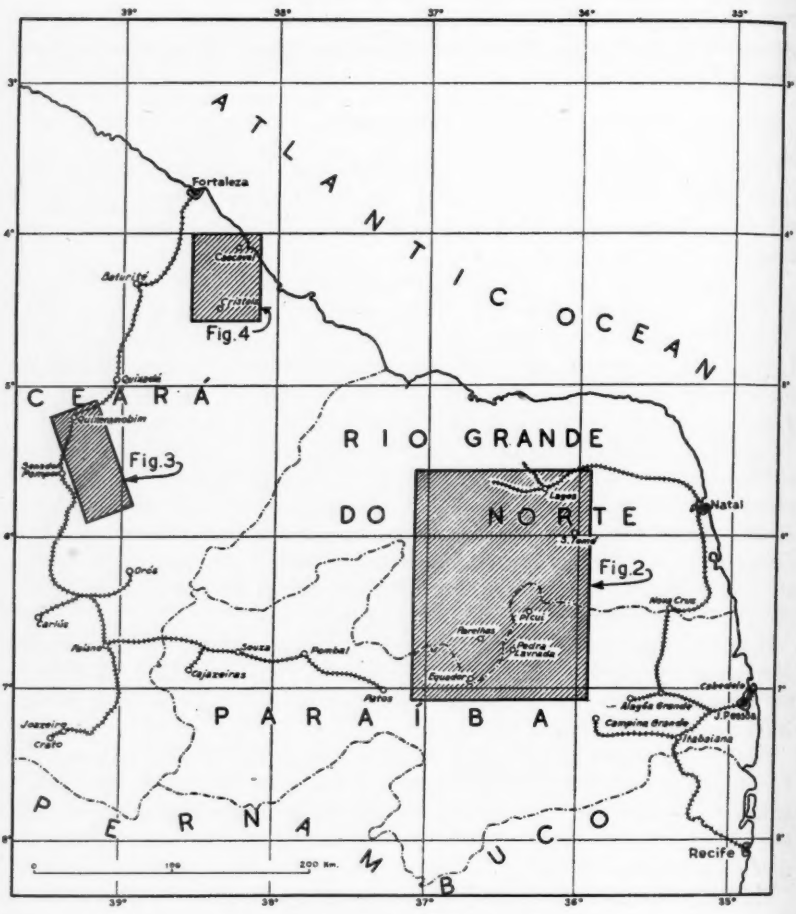

FIGURE 1.—*Index map of Northeastern Brazil*

Showing location of the pegmatite areas

The most complete accounts of the geology of the region were published by Crandall (1910) and Moraes (1924).

The rocks of Northeastern Ceará are pre-Cambrian schists with intercalated beds of quartzite and marble. They have been intruded by granites and cut by many pegmatites. In places, the schists have been granitized and assume the aspect of a gneiss. Crandall (1910, p. 21) named these schists the "Ceará series", and Guimarães

(1924, vol. 2, p. 115-117) pointed out their similarity to the Minas series of the state of Minas Gerais. Morais (1924, vol. 2, p. 29–44) restricted the use of Ceará series to exclude the rocks of the crystalline complex to which he had assigned the Seridó-

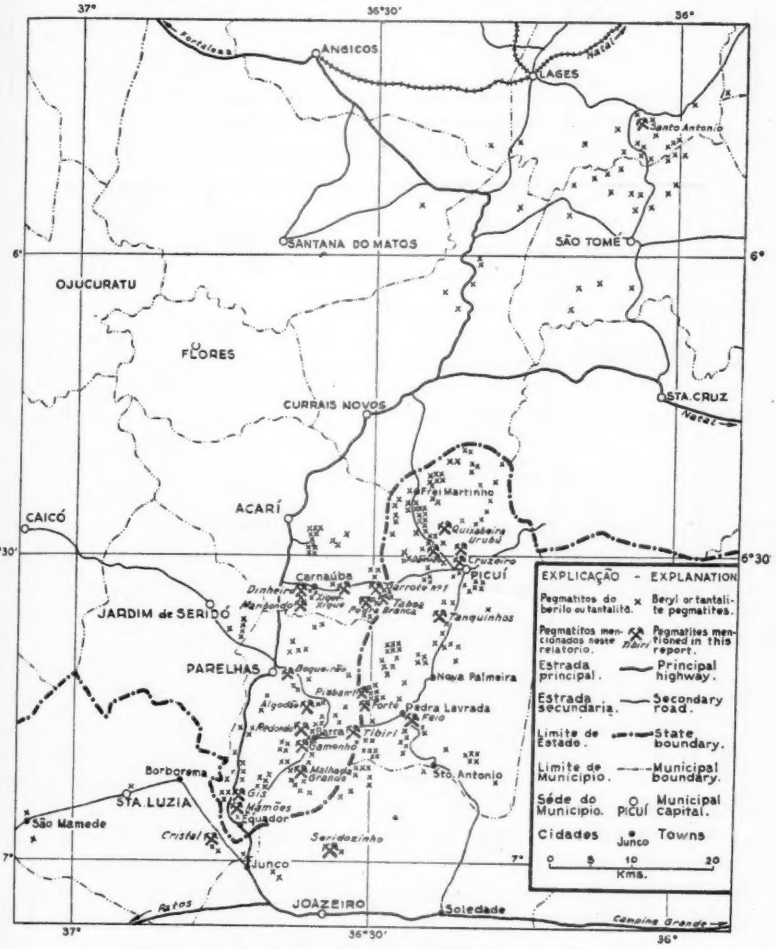

FIGURE 2.—*Index map of Paraiba and Rio Grande do Norte*

Showing the distribution of tantalite-beryl pegmatites

schist of Rio Grande do Norte. Probably a broader application of Guimarães' (1924, vol. 2, p. 115) principle of granitization may do much to break down the rigid concept of a basal crystalline complex in the Northeast. I see little difference between the Seridó schist at its type locality in Rio Grande do Norte and similar mica schist of the Quixeramobim-Cachoeira area in Ceará.

FIGURE 3.—*Index map of the Quixeramobim-Cachoeira area, Ceará*
Showing the distribution of beryl-amblygonite-tantalite pegmatites (×)

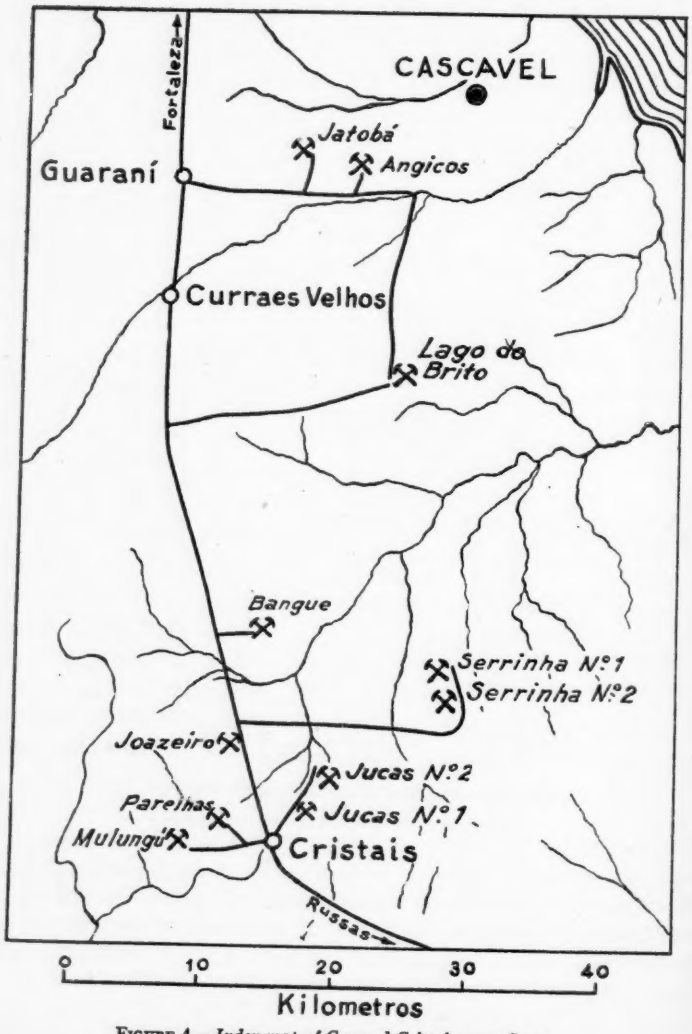

FIGURE 4.—*Index map of Cascavel-Cristais area, Ceará*
Showing the distribution of beryl-amblygonite-tantalite pegmatites

The pre-Cretaceous peneplane, so well preserved in the Picuí region of Paraíba, is represented in Northeastern Ceará by many monadnocks which rise above the rolling surface of the present erosion cycle. They lack, however, the flat tops and characteristic aspects of the Borborema plateau to the east. Because of the gently rolling terrain in Ceará, the pegmatites generally lack topographic expression save for a residual blanket of quartz fragments.

SERIDO SCHIST

The Seridó schist of Moraes consists of a great thickness of biotite-quartz and muscovite-quartz schists. It is widely distributed throughout the area and is the most common wall rock of the altos. It is gray to black and medium-grained. Interbedded in this schist are grey to yellow quartzites, such as are exposed on the highway between Junco and Equador and form the wall rock of Alto Mamões, and east of Carnaúba into which the Xique-Xique pegmatite was intruded. Also interbedded in the schists are thin marble layers, some of which have been the hosts for the contact-metamorphic scheelite deposits of the area.

Near the centers of granitic intrusion, as along the principal highway north of the Acarí dam, the Seridó schist has been granitized and assumes the aspect of a gneiss. Feldspars are introduced into the schist, *lit-par-lit* pegmatites cut it, and characteristic schist grades into fresh granite.

GRANITES

Many granite masses are intruded into the Seridó schist. They are widely distributed over the area shown in Figure 2. Most are of batholithic dimensions, such as the granite mass at Acarí which covers an area of about 50 square kilometers. The Acarí granite is gray and is composed essentially of microcline, quartz, and biotite. Its texture ranges from medium- to coarse-grained, and it has a porphyritic phase with large pink microcline phenocrysts.

Other granites in the area range from gray to pink and show great variation in grain size and foliation.

Guimarães (1924, vol. 1, p. 88–117) has described many of these types as well as monzonites and diorites from the area.

In addition to the granitization of the Seridó schist, many phenomena of contact metamorphism have resulted from the granitic intrusion. Tactites, some of which carry scheelite, were developed in the limestones interbedded in the schists; and zones of coarse biotite are developed in the schist near the centers of intrusion.

Lack of detailed geologic mapping prevents relating the pegmatites to any particular granite masses. In general, however, the pegmatites are in the schists and not in the granites, suggesting that they were intruded in an environment somewhat remote from the centers of granite intrusion where, possibly, conditions of temperature and pressure were less intense.

YOUNGER SANDSTONES

In the Picuí-Parelhas area, many remnants of the old peneplane are capped by cross-bedded sandstones of Upper Cretaceous (Crandall, 1910, p. 25–30) or possible Pliocene (Moraes, 1924, vol. 2, p. 50) age.

The road eastward from Picuí (Fig. 2) crosses an excellent exposure of a basal conglomerate composed of large angular quartz fragments, some of which contain tourmaline such as would be yielded by the pegmatites and quartz veins of the region. This conglomerate grades upward into a cross-bedded sandstone.

Other peneplane remnants are capped by several meters of a limonite conglomerate, locally called "canga", that probably represents a residual accumulation of iron derived from the weathering of the underlying biotite schists and brought to the surface by capillary action.

DIABASE DIKES

There are many small diabase dikes in the area, and near Lages are several basalt flows. At Alta Quixabeira (Fig. 30), north of Picuí, a diabase dike cuts the pegmatite. Moraes (1924, vol. 1, p. 39) noted that these dikes cut Cretaceous sediments.

PHYSIOGRAPHIC HISTORY

An older cycle of erosion is recorded in the Borborema peneplane that was developed in pre-Cretaceous time. This peneplane is well developed between Campina Grande and Joazeiro, where the local relief, due principally to the greater hardness of granitic rocks, is of the order of 100 meters. Farther north, in the vicinity of Picuí, remnants of the peneplane are conspicuous because of their flat tops. The elevation of the central part of the Borborema peneplane ranges from 550 meters at Campina Grande to 600 meters in the Serra de Santana north of Currais Novos. To the north it slopes to the sea.

As has been described in a previous section, parts of this peneplane are covered by younger sandstones with a basal conglomerate composed of quartz debris.

The present erosion cycle has cut into the Borborema peneplane giving steep slopes and drainage with high grades.

One consequence of these two erosion cycles is that pegmatites, such as Seridózinho (Fig. 31), that are on the old peneplane have little or no topographic expression, and, in many of them, the feldspars have weathered to kaolin; whereas pegmatites exposed in the present erosion cycle, because of the resistance of their quartz cores to weathering, have strong topographic expression, and, because of the comparatively recent date of their uncovering, the feldspars are fresh. Many pegmatites, such as Tabôa (Fig. 32), are on the flanks of outlying erosion remnants of the old peneplane.

PEGMATITES

CLASSIFICATION

The dikes of the region are granite pegmatites, consisting, essentially, of muscovite, quartz, and microcline that has been replaced in varying degrees by albite.

Some dikes are tabular bodies, 1–2 meters wide, and up to several hundred meters in outcrop length, whereas others are rounded or lens-shaped bodies, the largest of which are 500 meters in outcrop length and 100 meters in outcrop width. In the region, the narrow tabular dikes are numbered in the tens of thousands and the lens-shaped dikes in the thousands.

FIGURE 1. HOMOGENEOUS DIKE NEAR PICUÍ, PARAÍBA

FIGURE 2. ALTO PEDRA BRANCA, ACARÍ, RIO GRANDE DO NORTE
General view of a heterogeneous pegmatite showing the quartz core.

FIGURE 3. ALTO PEDRA BRANCA, ACARÍ, RIO GRANDE DO NORTE
Near view of the quartz core.

HOMOGENEOUS AND HETEROGENEOUS PEGMATITES

FIGURE 1. ALTO GARROTE No. 1, ACARÍ, RIO GRANDE DO NORTE
This is a characteristic heterogeneous pegmatite with strong topographic expression.

FIGURE 2. ALTO PIABA No. 1, PICUÍ, PARAÍBA
General view showing the method of mining.

FIGURE 3. SOLEDADE, CACHOEIRA, CEARÁ
This view is characteristic of the heterogeneous pegmatites of Ceará, which have but little relief.

FIGURE 4. BELO HORIZONTE No. 2, CACHOEIRA, CEARÁ
The Ceará pegmatites have little topographic expression.

HETEROGENEOUS PEGMATITES

The principal difference between the two types is in the degree of internal differentiation. The tabular dikes, in general, have a fairly uniform texture from wall to center and do not contain crystals of remarkable size; because of this uniformity, they have been designated homogeneous dikes. The lens-shaped dikes, on the other hand, show a high degree of differentiation with walls of muscovite, gigantic crystals of microcline in the interior of the dike, and a central core or nucleus of quartz. These highly differentiated pegmatites are designated heterogeneous dikes.

Both types are composed of the same essential minerals, and there appears to be no field evidence suggesting that they were derived from different sources. The heterogeneous dikes, whose essential minerals—microcline and quartz—occur in enormous crystals, are of economic interest because their accessory minerals—tantalite, beryl, cassiterite, spodumene, and amblygonite—also occur in unusually large crystals.

Unfortunately, no detailed study of the accessory minerals of the homogeneous dikes has yet been made. The most direct approach to such a study would be to mine, crush, and table several large samples of homogeneous dikes and to study the heavy concentrates so derived. Equipment for such a study has not been available in the area.

This classification, originally applied to the pegmatites of Paraíba and Rio Grande do Norte, appears to be applicable to Ceará with the qualification, that very few of the Ceará pegmatites show the high degree of differentiation exhibited, for example, by Alto Feio or Alto Tanquinhos, of Paraíba. Most of the producing Ceará pegmatites are comparatively poorly differentiated and would fall, perhaps, into a classification midway between homogeneous and heterogeneous as used in the Picuí-Parelhas area.

FORM AND SIZE

Plane-table maps were made of 21 producing pegmatites in the Picuí-Pare has area on a field scale of 1 to 1000. In Figure 5 these 21 pegmatites are shown on the same reduced scale and in the same orientation. The outcrop area of the quartz core is also shown.

Plane-table maps were also made of 10 pegmatites in the Quixeramobim-Cachoeira area on a field scale of 1 to 500 and are shown on the same reduced scale and in the same orientation in figure 6. Alto Boqueirão in Rio Grande do Norte is also shown in figure 6 for comparison with the Picuí-Parelhas pegmatites (Fig. 5).

The largest altos are Feio, whose outcrop dimensions are 500 by 100 meters, and Tanquinhos, which is 400 by 100 meters. Manões, another big alto, is about 450 by 30 meters in outcrop dimensions. Dinheiro, which is conspicuous because of its wall-like outcrop, is 180 meters long by 12 meters wide and 23 meters high.

Because of the resistance to erosion of the quartz core, many altos stand in relief. Some of the larger altos in the Picuí-Parelhas area rise as much as 50 meters above the softer surrounding rocks.

In Ceará, however, the pegmatites have little topographic expression as they generally have been eroded to the same level as their enclosing rocks (Pl. 2, figs. 3, 4).

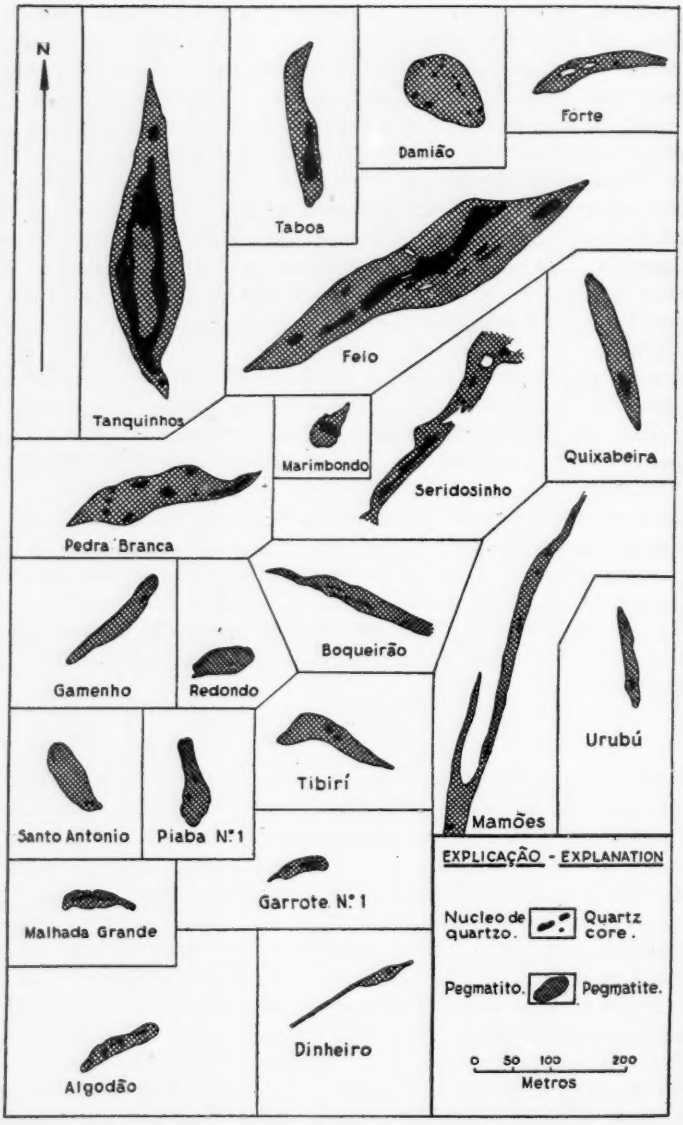

FIGURE 5.—*Plan diagram of Paraiba and Rio Grande do Norte pegmatites*
Showing the size, shape, and orientation of the pegmatites

In general, the heterogeneous dikes or altos form flattened disks. The dip of the walls and the position of the various mineral zones enable one to determine whether the top or the bottom of a pegmatite disk is exposed. Thus, Piaba No. 1 (Fig. 29)

and Redondo have just been uncovered by erosion, and most of the pegmatite body remains; whereas Damião (Fig. 19), Garrote No. 1, and Tanquinhos (Figs. 33, 34) represent the lower parts of pegmatite bodies whose tops have been eroded.

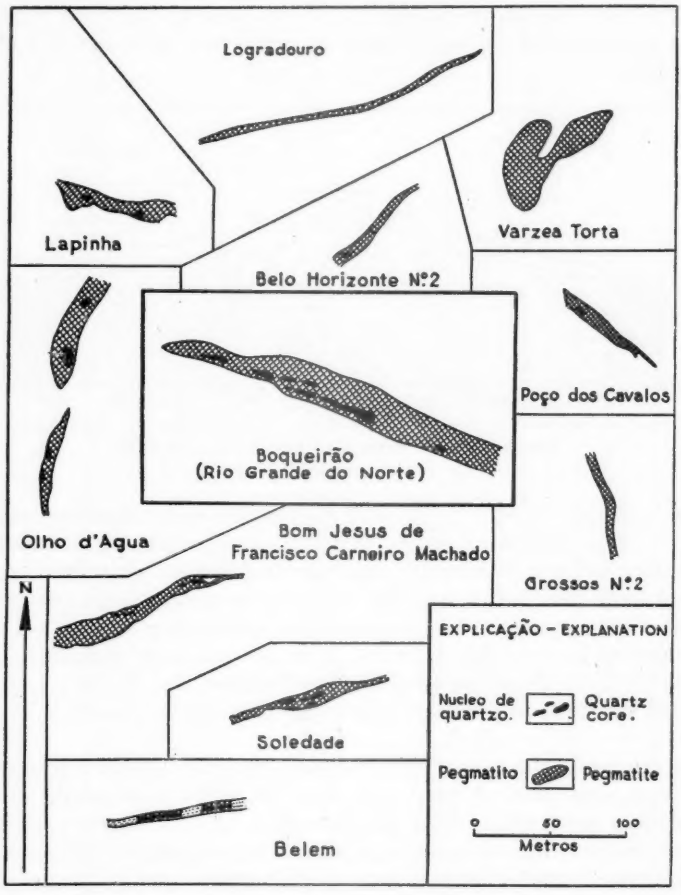

FIGURE 6.—*Plan diagram of Ceará pegmatite*

Showing the size, shape, and orientation of the pegmatites of the Quixeramobim-Cachoeira area, Ceará, described in this report. Alto Boqueirão, Rio Grande do Norte, is here included to facilitate comparison with Figure 5.

In general, the disklike bodies stand vertically, but some, such as Pedra Branca (Fig. 28), are inclined, and some, such as the small pegmatite near Equador (Fig. 8), lie approximately horizontal.

RELATION TO REGIONAL STRUCTURE

Most pegmatite disks have their long axes parallel to the regional schistosity. However, many, such as Dinheiro, Forte (Fig. 24), Gamenho, and Malhada Grande

(Fig. 27) transect the regional schistosity at low angles; and some such as Algodão, Garrote No. 1, and Tibiri have their long axis transverse to the regional schistosity.

INTERNAL ZONING

Figure 7 is a diagrammatic sketch showing the four mineral zones which characterize the highly differential heterogeneous pegmatites. Generally all four zones are present.

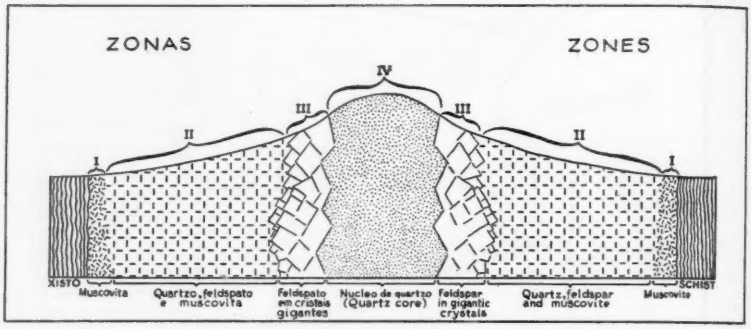

FIGURE 7.—*Generalized sketch of a heterogeneous pegmatite*
Showing the four zones

Zone I, on the walls of the pegmatite, is characterized by abundant muscovite, usually in large crystals. It is best developed in pegmatites which intruded the Seridó schist and may be absent in pegmatites intruded into quartzites. For that reason it seems possible that the schist may have contributed to the chemical composition of the muscovite. This zone usually is less than 1 meter wide and may be only a few centimeters (Figs. 8, 13, 20, 23, 26, 34). In some pegmatites, such as Damião (Pl. 3, fig. 2) and the small dike near Equador (Fig. 8), this zone contains much black tourmaline. In some pegmatites, cassiterite occurs with mica in this zone.

Zone II consists of a normal feldspar-muscovite-quartz pegmatite identical with the homogeneous dikes. In places this zone has graphic intergrowths of quartz and feldspars and rarely, as at Piaba No. 1 (Pl. 4, fig. 3), it contains long narrow blades of biotite. This zone constitutes most of the pegmatites. With increase in size of feldspar crystals it grades into the next innermost zone.

Zone III is characterized by a predominance of large feldspar crystals, which may attain dimensions measured in meters and weight measured in tons. (Figs. 9, 10, 20, 22; Pl. 3, fig. 1). Most of the beryl, tantalite, and spodumene comes from this zone.

Zone IV, which generally forms the center of the pegmatite, is characterized by large bodies of milky or rose quartz (Figs. 9, 22; Pl. 1, figs. 2, 3). In some pegmatites, the quartz contains vugs lined with quartz crystals (Pl. 4, fig. 1). Commonly this zone yields beryl, often in very large crystals.

Figure 8 is a sketch of a small pegmatite exposed in a road cut near Equador. It clearly shows, on a small scale, the four characteristic zones.

(Road surface) Leito da estrada
Nucleo de quartzo (Quartz core)
Microclina em cristais grandes (Large crystals of microcline)
Turmalina (Negra) (Tourmaline (Black)
Feldspato, quartzo e muscovita (Feldspar, quartz and muscovite)
Muscovita (Muscovite)
Xisto de Seridó (Seridó Schist)
0 2 4
Metros

FIGURE 8.—*Sketch section of a small flat-lying heterogeneous pegmatite*
In a road cut near Equador, Rio Grande do Norte

In general, within the pegmatites of the Picuí-Parelhas area, zone I yields mica and cassiterite; zone III yields tantalite, beryl, and spodumene; and zone IV yields beryl and, more rarely, smaller quantites of tantalite and spodumene.

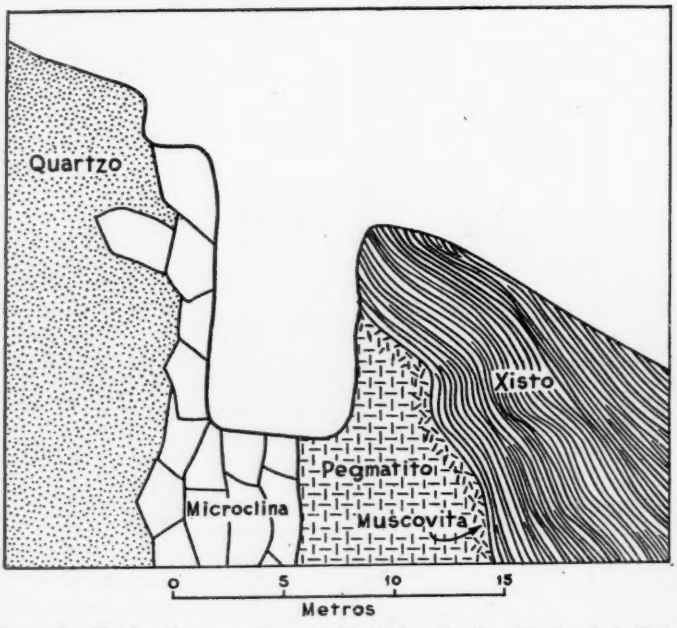

FIGURE 9.—*Sketch section across the west half of Taboa, Parelhas, Rio Grande do Norte*

Showing zones I to IV

In the Ceará pegmatites, zone I yields muscovite and, rarely, beryl; zone II yields some beryl and amblygonite; zone III yields the greater quantity of beryl, amblygonite, and tantalite; and zone IV is barren.

The zoning appears to have resulted from progressive cavity filling and represents, in general, the dominant order of crystallization of the pegmatite minerals.

MINERALOGY

Essential minerals.—The essential minerals of the heterogeneous pegmatites are muscovite, quartz, and microcline.

MICAS: Muscovite occurs in all four zones. It is most abundant in zone I where commonly it occurs in large books that yield a commercial product. Small mica shops have operated at Pedra Lavrada and Picuí. In zones II and III the muscovite generally is in smaller books. In zone III commonly it forms small isolated rosettes and clusters or large masses of small books in random orientation (Pl. 3, fig. 1). Much of the mica in this zone, as at Alto Feio, is pale yellow. In many of the larger pegmatites, as Boqueirão (Fig. 10), Feio (Fig. 22), Tabôa, and Tanquinhos, it forms clusters in the center of microcline crystals that are partically replaced by albite. It seems more

FIGURE 1. ALTO FEIO, PICUÍ, PARAÍBA
Longitudinal section of the pegmatite along the interfingered boundary between zones III and IV.

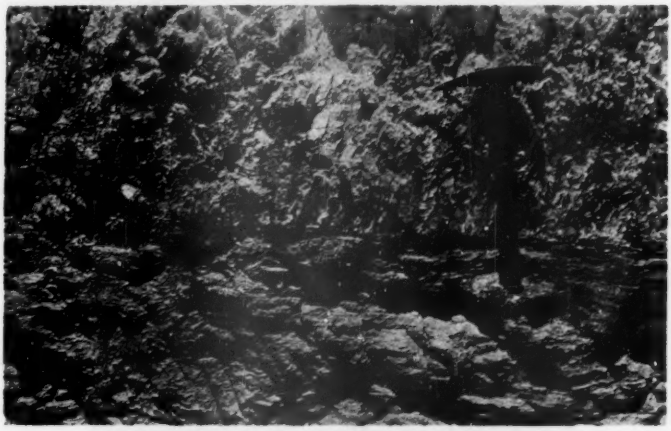

FIGURE 2. ALTO DAMIÃO, PICUÍ, PARAÍBA
Tourmaline and muscovite in zone I of the pegmatite in contact with the schist floor.

FIGURE 3. VÁRZEA TORTA, CACHOEIRA, CEARÁ
View showing coarse muscovite at the schist contact.

MINERALOGIC DETAIL OF HETEROGENEOUS PEGMATITES

FIGURE 1. ALTO BOQUEIRÃO, PARELHAS, RIO GRANDE DO NERTE
Quartz crystals from a vug in the quartz core. The largest weighs about 200 kgrs.

FIGURE 2. ALTO MARIMBONDO, ACARÍ, RIO GRANDE DO NORTE
Large spodumene crystals (white) in albitized microcline (gray). Spodumene crystal at bottom of photograph is about 1 meter long.

FIGURE 3. ALTO PAÍBA NO. 1, PICUÍ, PARAÍBA
Bladed crystals of biotite in zone II.

MINERALOGIC DETAIL OF HETEROGENEOUS PEGMATITES

probable that muscovite was contemporaneous with the nuclei of the microcline crystals and that its crystallization stopped before the microcline crystals had attained their full growth rather than that the muscovite was introduced into the centers of microcline crystals when they were albitized. At Tanquinhos and at some of the smaller altos, a narrow band of muscovite occurs between large crystals of microcline and adjacent masses of milky quartz. In zone IV, mica occurs in isolated books or small clusters, but it is not abundant.

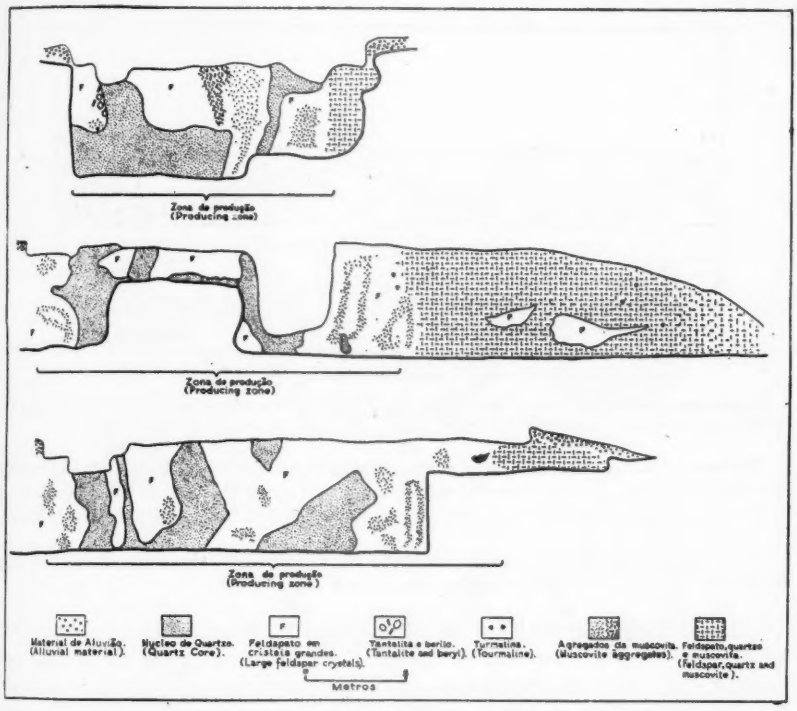

FIGURE 10.—*Sketch sections of the Boqueirão mine, Parelhas, Rio Grande do Norte*

Showing large feldspar crystals intergrown with muscovite

Biotite, in long bladed crystals, is the most conspicuous mineral at zone II at Piaba No. 1 (Pl. 4, fig. 3). Similar biotite blades were observed in the same zone at Tanquinhos, Cabeceira, and Tonica. In general, however, biotite is an essential mineral in only a few of the heterogeneous pegmatites.

A small amount of lilac-colored lepidolite was found at Boqueirão.

QUARTZ: Quartz is an abundant constituent of all four zones. The quartz cores, which constitute zone IV, are sometimes very large (Fig. 5) and commonly contain vugs lined with euhedral crystals as at Boqueirão (Pl. 4, fig. 1), where the largest crystal observed weighed about 200 kilogram. Generally the quartz is milky, but rose quartz is not uncommon. At Alto Feio, uerally the quartz is erally the quarz is milky, but rose quarz is not uncommon. At Alto Feio, much of the core is rose quartz, and some of it has a very deep color. Bluish quartz occurs at Alta Serra Branca which also contains both smoky quartz and citrine. Much of the quartz is traversed by faint planes which generally converge and intersect at low angles. Under the microscope, some of these planes are seen to be composed of many minute inclusions and vacuoles, some of which contain liquid and a

gas bubble. Other planes are lines of shearing where the quartz is brecciated and recemented by other quartz.

FELDSPARS: The original feldspar of the heterogeneous pegmatites is microcline. It may be white, cream, salmon, or pink. In all specimens examined under the microscope, the microcline had been replaced to some degree by albite, which, in general, did not change the original color of the microcline. Albitization progresses along the cleavages of the microcline, and, in general, the centers of large microcline crystals are less albitized than their peripheries.

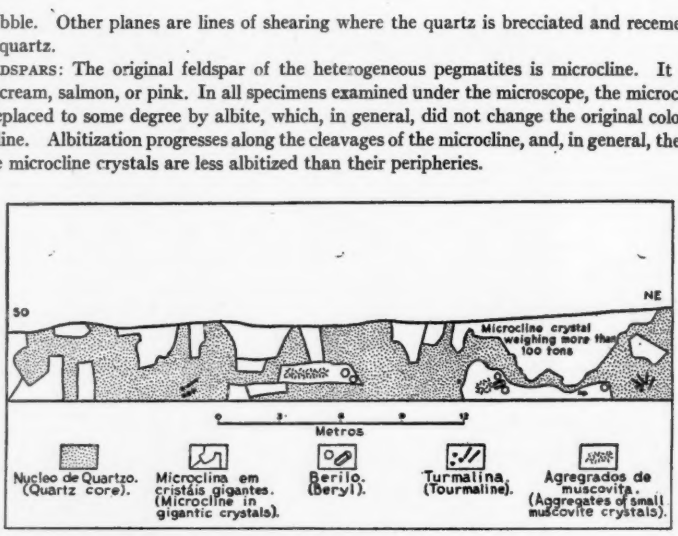

FIGURE 11.—*Sketch section at Alto Feio, Picuí, Paraíba*

Showing gigantic microcline crystal. This section is parallel with the long axis of the alto and passes through the interfingered contact between zones III and IV.

The lamellar variety of albite known as cleavelandite is present in some altos. At Tanquinhos it occurs in large thin crystals in zone III at the contact with the quartz core. It is also conspicuous at Alto Marimbondo, where it is associated with spodumene, and in Poço dos Cavalos and Mulungú, in Ceará.

Albitization came fairly late in the sequence of mineral deposition of the pegmatites and appears to bear no relation to the distribution of tantalite, beryl, and cassiterite.

Accessory minerals.—With the exception of quartz, micas, and feldspars, all the minerals of the pegmatites can be considered as accessories. We are accustomed to think of accessory minerals as minute inclusions, such as zircon, rutile, and apatite, in crystals of quartz or feldspar whose dimensions are measured in millimeters, or at most, in centimeters. But in the pegmatites of the Northeast the essential minerals occur in crystals measured in meters, and the accessory minerals, such as beryl and tantalite, commonly conform to this gigantic scale.

BERYL: The heterogeneous pegmatites of the area have yielded about 8000 tons of beryl of which 700 tons came from Ceará. The theoretical BeO content of beryl is 14 per cent. Representative shipments, as shown in Table 1, range from 11 to 13 per cent BeO, the remainder being gange material, principally feldspars.

Beryl occurs principally in zone III on the border of zone IV. As shown in Figures 10, 11, and 22, it usually is imbedded in large feldspar crystals or in a mixture of feldspar and muscovite. Commonly isolated crystals are found in the quartz core, as at the south end of Alto Tanquinhos. Such crystals are often fractured and healed by quartz.

Beryl crystals with inclusions of microcline, quartz, muscovite, and tourmaline (Fig. 12) are not rare. These occur in zone III and represent a contemporaneous intergrowth of beryl with the other minerals. There is no internal evidence to justify interpreting such intergrowths as due to the re-

TABLE 1.—*Analyses of beryl shipments*
(Ledoux & Co., New York)

Date of analysis	Weight of shipment (Pounds)	BeO (Per cent)
April 21, 1943	216,983	11.31
April 21, 1943	55,337	12.35
May 16, 1944	54,225	12.97
May 16, 1944	76,140	12.61
June 19, 1944	53,480	11.87
June 19, 1944	53,926	12.34
June 19, 1944	54,170	11.95
June 19, 1944	53,880	12.48

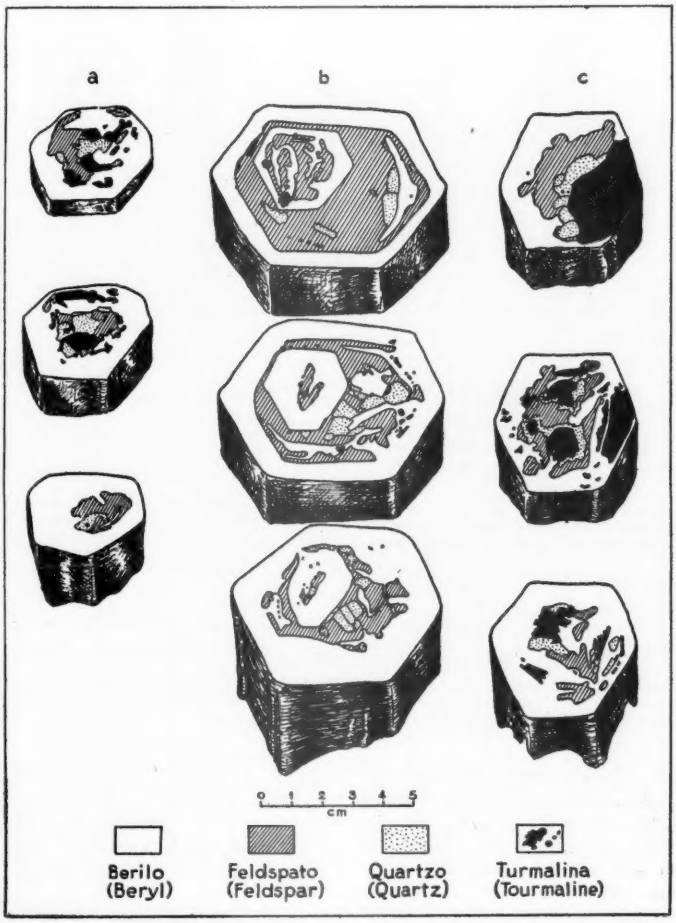

FIGURE 12.—*Drawings of three beryl crystals from Alto Cruzeiro, Picuí, Paraíba*
Showing intergrowth of feldspar (microcline partially albitized), quartz, and tourmaline

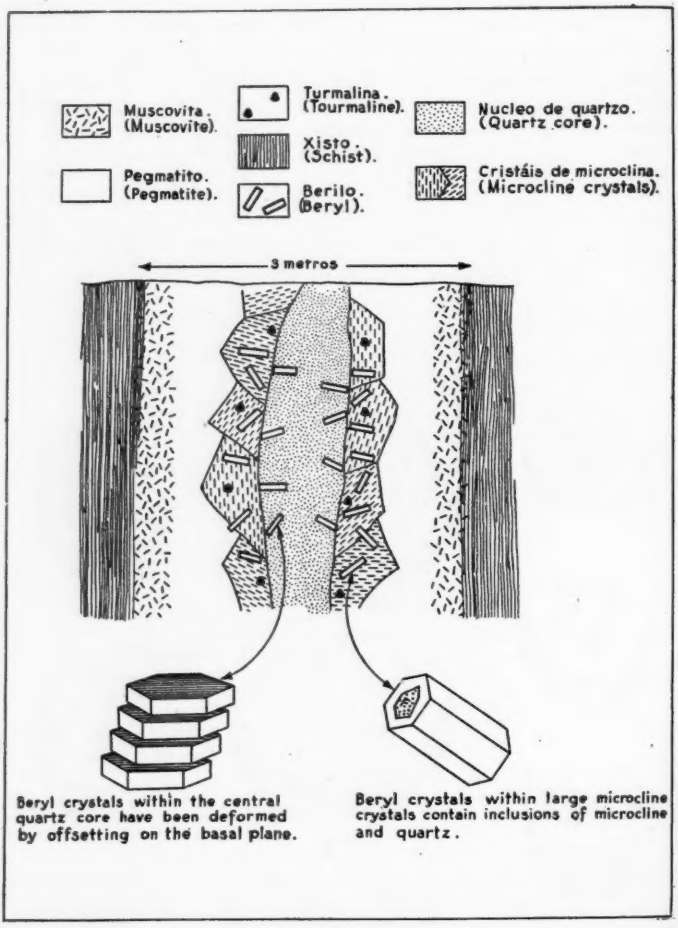
Muscovita. (Muscovite).
Turmalina. (Tourmaline).
Nucleo de quartzo. (Quartz core).
Xisto. (Schist).
Pegmatito. (Pegmatite).
Berilo. (Beryl).
Cristáis de microclina. (Microcline crystals).
3 metros
Beryl crystals within the central quartz core have been deformed by offsetting on the basal plane.
Beryl crystals within large microcline crystals contain inclusions of microcline and quartz.

FIGURE 13.—*Diagrammatic sketch of Morada Nova mine, municipality of Parelhas, Rio Grande do Norte*

Showing position in the pegmatite of (a) beryl crystals that have been deformed mechanically by repeated offsetting on the basal plane which are found within the central quartz core and (b) beryl crystals with inclusions of microcline and quartz, which are found in the large microcline crystals bordering the quartz core.

placement of feldspar, quartz, and tourmaline by beryl. Morada Nova, a small pegmatite near Parelhas, has yielded many interesting specimens of both beryl intergrown with other minerals and beryl crystals offset on the base, such as are commonly illustrated in textbooks on crystallography. As is sketched in Figure 13, beryl with inclusions is confined to zone III, whereas the beryl crystals that have been curved by repeated basal offsetting occur in zone IV and record movement within that zone.

Beryl crystals range from a few millimeters to a meter or more in diameter. Casts of crystals which weighed several tons can be seen in the quartz on the north side of Alto Feio.

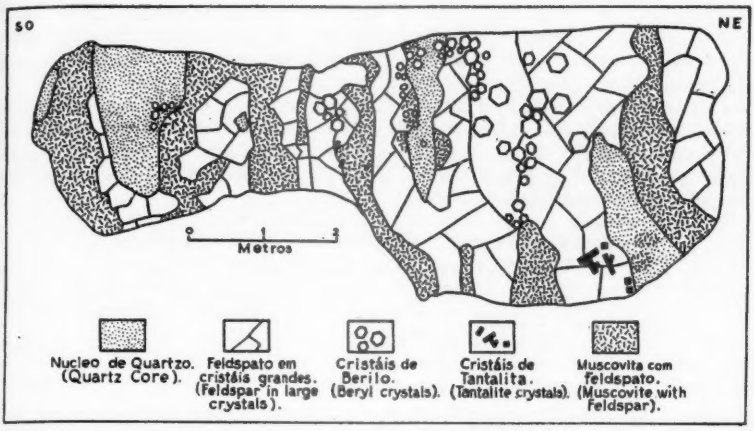

FIGURE 14.—*Sketch of an underground face on the west side of Tanquinhos, Picuí, Paraíba*
This pocket yielded more than 100 tons of beryl and 1 ton of tantalite

TABLE 2.—*Analyses of tantalite shipments*
(Ledoux & Co., New York)

Date of analysis	Weight of shipment (Pounds)	Ta_2O_5 (Per cent)	Nb_2O_5 (Per cent)	TiO (Per cent)	SnO (Per cent)
Nov. 6, 1942	10,130	57.46	20.73	1.88	1.66
Nov. 10, 1942	11,036	54.97	23.05	1.88	1.79
Feb. 4, 1943	10,969	62.36	15.81	1.80	1.85
May 28, 1943	13,179	46.41	30.32	2.16	1.02
June 28, 1943	10,961	67.52	11.28	1.76	1.27
July 26, 1943	2,420	62.10	16.08	2.00	1.61
Sept. 7, 1943	43,742	40.74	32.95	2.64	2.45
July 11, 1944	6,549	61.20	18.31	0.80	1.42
July 20, 1944	2,204	31.89	31.13	3.36	13.39
July 20, 1944	3,623	45.23	27.86	2.96	2.12
July 20, 1944	2,229	52.62	23.16	2.80	2.45
July 31, 1944	6,678	47.92	25.74	3.84	1.04

The richest aggregate of beryl crystals in the region was found at the Tanquinhos mine and is sketched in Figure 14. More than 100 tons of beryl were recovered from this pocket.

Most of the beryl is opaque. Light green is the most common color, but much of it is cream-colored, white, light blue, or pink. Occasional crystals yield small pieces of light-colored aquamarine, but these are not common. No good gem beryl has been found in the region.

TANTALITE-COLUMBITE: These minerals are isomorphic tantalates and niobates of iron and manganese. The specific gravity ranges from 5.5 to 7.0, the streak from medium brown to black, and the luster of a fresh surface from brilliant to dull. The high tantalite ores are characterized by a high specific gravity, brown streak, and a brilliant luster; whereas the high columbite ores have a lower specific gravity, a black streak, and a dull luster. Many ore sorters have acquired a remarkable degree of skill in classifying these minerals.

Representative shipments, as shown in Table 2, range from 32 to 67 per cent Ta_2O_5.

These analyses, of course, are of ore shipments which are mixtures of tantalite from many altos.

Since the first shipments in 1938, the pegmatites of the region have yielded about 600 metric tons of tantalite.

Tantalite occurs in the feldspars of zone III and more rarely in the outer margins of zone IV. Most of the workings in the altos are in the big feldspar, and the quartz core forms the innermost wall of the excavation (Figs. 14, 26). Generally it occurs in small crystals of a few grams, but crystals at the Tanquinhos mine (Fig. 14) yielded more than a ton of tantalite.

In a few altos, such as at Malhada Grande, tantalite occurs in very small crystals disseminated in completely albitized feldspar. This occurrence, when viewed alone, suggests that the deposition of tantalite is associated with the process of albitization. In my opinion, however, such a conclusion is not justified in view of the general distribution of tantalite on the inner margin of the zone of big feldspars in some of which albitization is weak.

TABLE 3.—*Analysis of "manganotantalite" from Alto Boa Vista*
(Polin Laboratory, Rio de Janeiro)

	Per cent
Ta_2O_5	73.5
Nb_2O_5	2.3
TiO_2	0.2
SnO_2	nil

Much of the tantalite production of the area has been recovered from placers. These are confined to the slopes of the altos and do not extend far from their bases. No stream placers of tantalite have been found. Some preliminary investigations were made of the placer possibilities of the valley of the Rio Potengí, near São Tomé, where there are many homogeneous and a few heterogeneous pegmatites. As it is shown in Figure 15, a few shallow test pits were sunk on the river bank which yielded a small quantity of black sands consisting mainly of ilmenite and no tantalite. As the pits did not reach bed rock, the test was not conclusive.

The highest niobium content yet found in Northeastern Brazil was given by an 800-kilogram sample from the Serra mine, near Cachoeira, Ceará, which yielded 57.2 per cent Ni_2O_5 and 16.6 per cent Ta_2O_5.

Some altos principally in the neighborhood of Equador, yield occasional dark-red translucent crystals of high tantalum content. This mineral is provisionally identified as manganotantalite, but, to my knowledge, no complete analyses have been made. A sample of this mineral from the Alto Boa Vista was partially analyzed by the Polin Laboratory in Rio de Janeiro (Table 3).

There is need for rigorous mineralogical studies of the tantalum-niobium minerals of the Northeast. It is to be hoped that the chemical work of the Departamento Nacional da Produção Mineral and additional chemical and mineralogical investigations of Brazilian specimens by the Fansteel Metallurgical Corporation soon will be published.

MICROLITE: Minerals from two pegmatites have been identified, as microlite—the calcium tantalate. At Alto Onça, near Pedra Lavrada, a dull white to cream-colored mineral occurs as a crust around tantalite. In some specimens, this mineral surrounds isolated subangular pieces of tantalite giving a characteristic alteration or replacement texture. An excellent example, showing this alteration texture, which bears a close resemblance to a specimen formerly in my mineral collection in Rio de Janeiro, has been figured by Pough (1945a, Pl. 4, fig. 1). This alto produced about 1.5 metric tons of tantalite with its accompanying alteration product, which was shipped as tantalum ore. A partial analysis of a specimen of this material, containing only a few fragments of tantalite is given (Table 4).

The second locality yielding provisional microlite are the adjoining altos Gis and Mamões, near Equador. Only a few kilograms of this material have been found, and most of that has been shipped with tantalite. The mineral is white to pale yellow, with a vitreous luster and a hardness of about 6. Under the ultra-violet lamp it fluoresces a pale blue, a property which the earthy microlite from Alto Onça does not share. Tests at the Campina Grande laboratory confirm the presence of calcium.

There are unconfirmed accounts that small quantities of this mineral have been found in a few other altos near Equador.

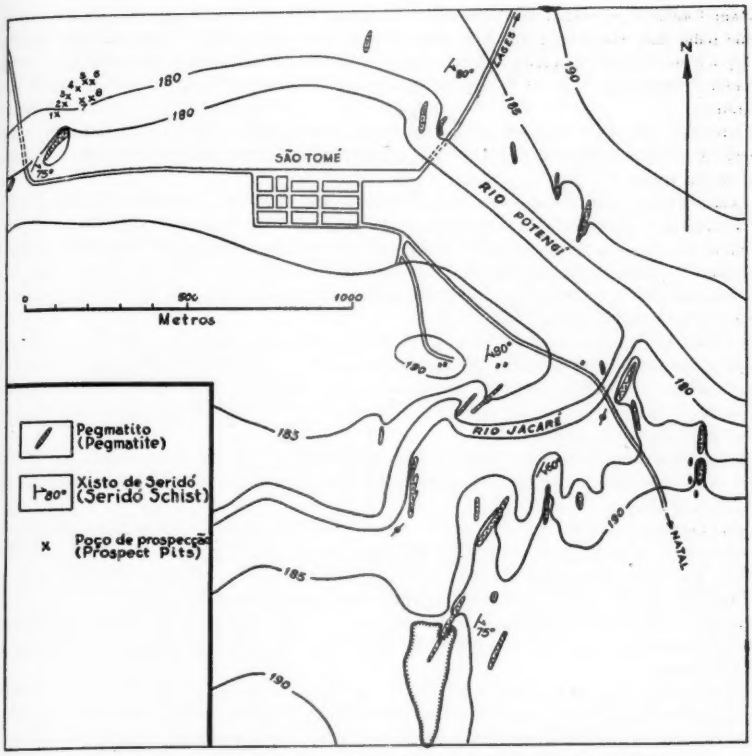

FIGURE 15.—*Sketch map of the vicinity of São Tomé, Rio Grande do Norte*

Placer prospecting here for tantalite yielded only ilmenite. The pegmatites shown are of the homogeneous type

TABLE 4.—*Analysis of microlite from Alto Onça*

(Polin Laboratory, Rio de Janeiro)

	Per cent
Ta_2O_5	74.0
Nb_2O_5	5.0
TiO_2	0.65
CaO	12.7

SIMPSONITE: In June 1942, Professor O. H. Leonardos obtained a few crystals of a new mineral from Equador, Paraíba. He sent them to Guimaraens who recognized them as an aluminum tantalate which he named "calogerasite" in 1942 and described in 1944, pointing out, at that time, its similarity to simpsonite. From two analyses, he assigned the formula $3Al_2O_3 \cdot 2Ta_2O_5$. In 1945, the excellent study of Kerr and Holmes definitely established its identity with simpsonite.

Alto Gis has produced, perhaps, 200 kilograms of this mineral, most of which was shipped as ore. Specimens which I examined were hexagonal, yellow to reddish, resinous, with a hardness of about 7. Under the ultraviolet light, simpsonite fluoresces bluish green. Photographs of some well-formed crystals are given by Rolff (1944c, p. 218), and Pough (1945b, Pl. 1) shows a beautiful color plate of simpsonite.

RARE EARTH TANTALATES AND NIOBATES: The pegmatites yield small quantities of many minerals of the polycrase, euxenite, samarskite group but, without adequate mineralogical and chemical study, it is not feasible to assign definite names to them. There is need for rigorous study of the minerals of this group from the Northeast, some of which appear to contain economic quantities of tantalum.

MONAZITE: Monazite is found in Alto Capoeiras, municipality of Santa Cruz, where it occurs in well-formed brownish-red crystals up to 5 cm. in breadth. It has also been found in pegmatites near Santa Luzia and Picuí.

CASSITERITE: Cassiterite occurs in many pegmatites in the area. It is mined commercially at the Seridózinho and Pedras Pretas pegmatites near Joazeiro where it occurs interleaved in the mica books of zone I. The mica is crushed and panned to recover the cassiterite. It also is found at Marimbondo, Malhada Grande, and Serra Branca. It is of interest to note that Seridózinho, Marimbondo, and Serra Branca also have spodumene. This association of tin and lithium is common elsewhere in the world (Hess, 1940).

LITHIUM MINERALS: About 300 tons of spodumene, averaging about 7 per cent Li_2O, have been shipped from the Seridózinho mine. As is shown in Almeida's map of Seridóinho (Fig. 31), the spodumene occurs in zone III and in the peripheral part of zone IV. Likewise at Alto Marimbondo (Pl. 4, fig. 2) spodumene is found in both zones III and IV. At both mines it forms crystals up to 2 meters or more in length.

About 1400 metric tons of amblygonite have been obtained from the Ceará pegmatites. A shipment of 53 tons made in August 1943 contained 8.43 per cent Li_2O. Amblygonite occurs in both zone II and III.

Spodumene is abundant in some of the pegmatites of the Picuí-Parelhas area, and amblygonite is relatively rare, small quantities having been found in only a few pegmatites in that area (Rolff, 1944b); whereas in Ceará amblygonite is common (Leonardos, 1942), and spodumene rare.

Lepidolite is rare in the Picuí-Parelhas area, being found principally at Alto Boqueirão. It is abundant in some of the Ceará pegmatites, notably at Lago do Brito, near Cristais, and Bolinha, near Quixeramobim. In the latter pegmatite it occurs in characteristic association with green and red tourmaline.

PHOSPHATES: Arrojadite (Guimarães, 1942), an iron-manganese phosphate of the wagnerite group, is a hard, dark-green, cleavable mineral occurring in many pegmatites. It alters to a dark-red to brown mineral with a characteristic red-violet streak and, in places, it also yields a mineral closely resembling vivianite. Arrojadite occurs in both zone III and IV. Many tons of this mineral have been found in the Serra Branca pegmatite.

Apatite has been identified in some of the pegmatites of the area, but it is not common. The crystals of apatite from Paraíba come from the municipality of Alagoa do Monteiro, in the southern part of the state (Johnston, 1944b).

URANIUM MINERALS: A small quantity of uranite (pitchblende) has been found in zone III in Xique-Xique, Boqueirão, and a few other altos. It occurs in rounded masses, generally small, surrounded by yellow, orange, and green alteration products of undetermined composition; but provisionally called gummite. The largest specimen obtained was from Alto Xique-Xique and weighed about 50 grams. Under ultraviolet light occasional masses of green fluorescent uranium minerals are seen. The amount of contained UO_3 in these pegmatites, however, is small.

Many pegmatites contain chalcedony with the yellow-green fluorescence characteristic of traces of contained uranium.

TOURMALINE: The black tourmaline aphrizite occurs in all zones, but in many pegmatites it is most abundant in zone I. Characteristic associations are shown in Figures 8, 10, 11, and 22. Large crystals are always badly fractured and fall to pieces when they are removed. Occasional crystals from zone IV are fractured and recemented by later quartz.

Graphic intergrowths of tourmaline and quartz were observed at a few altos in zone III.

At the Poço dos Cavalos pegmatite, near Cachoeira, Ceará, fine black tourmaline crystals are enclosed, in random orientation, in transparent quartz crystals weighing up to 20 kilograms each.

Gem tourmaline is relatively rare. Alto Feio has yielded a few kilograms of bottle-green transparent crystals. Fractures in the tourmaline crystals were filled with chalcedony. At the Bolinho pegmatite, near Quixeramobim, Ceará, tourmaline crystals with deep-red centers and green margins are fairly abundant, some of which yield dark rubellite of gem quality. Clear green tourmaline has been found in several other pegmatites in the Quixeramobim-Cachoeira area.

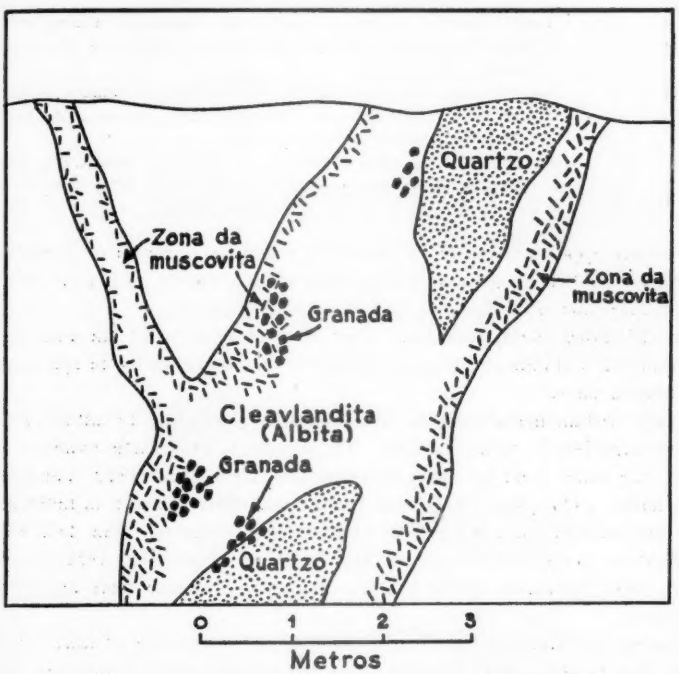

FIGURE 16.—*Sketch of a face at Poço dos Cavalos, Quixeramobim, Ceará*

Showing garnet in cleavelandite

GARNET: Two Ceará pegmatites, Poço dos Cavalos, near Cachoeira, and Mulungú, near Cristais contain a deep-red garnet, probably grossularite. In both mines it occurs with abundant clevelandite. At Poço dos Cavalos the garnet is mined for gem stones and cut in Rio de Janeiro. Some of the altos in the Picuí-Parelhas area contain occasional spessartite crystals that weather to manganese oxides.

BISMUTH MINERALS: Metallic bismuth is found in many pegmatites, generally as veinlets in quartz. Usually the bismuth is partially altered to bismutite.

SULPHIDES: Occasional sulphide minerals are found in many altos. Generally they occur in the quartz of zone IV and appear to have been introduced in the last phases of quartz deposition.

Pyrite, chalcopyrite, and chalcocite appear to have been the original iron and copper sulphides that were deposited. Rolff (1944a) has reported molybdenite from 10 altos in Paraíba and Rio Grande do Norte.

OTHER MINERALS: Illmenite, rutile, zircon (Rolff, 1944g), lazulite, magnetite, rhodonite, and copper carbonates also have been found in the pegmatites of the region.

ORIGIN

The internal zoning of the heterogeneous pegmatites of the region was discussed in an earlier section of this report. The four zones, passing from the walls toward the center are:

Zone	*Characteristics*
I	Large proportion of muscovite, with lesser amounts of feldspar and quartz.
II	"Normal" pegmatite composed of feldspars, muscovite (and sometimes biotite) and quartz.
III	Large crystals of feldspar (microcline) with smaller amounts of muscovite and quartz. The accessory minerals, such as tantalite and beryl, may also occur in relatively large crystals.
IV	Central core or nucleus of quartz with subsidiary amounts of muscovite and feldspar, some beryl and occasionally a little tantalite on the periphery.

This zoning appears to be the expression of a definite sequence of crystallization which resulted in the progressive filling, from walls to center, of the cavities which the pegmatites now occupy.

Figure 17 shows the approximate order of crystallization of the principal pegmatite minerals and indicates the relation of this time sequence to the space relations of the mineral zones.

The only certain major mineral replacement is microcline by albite, a process which occurred late in crystallization. There appears to be little evidence to substantiate the belief, held by many investigators (Hess, 1925; 1933; Landes, 1925; 1933; Schaller, 1925; 1927; 1933), that the mineral differentiation in heterogeneous pegmatites resulted from a series of complex replacements. The field evidence appears rather to confirm the opinion held by others (Fersmann, 1931; Quirke and Kermers, 1943; Uspensky, 1943) that the pegmatite minerals were deposited in a single cycle.

The excess muscovite of zone I appears to be a consequence of mica schist wall rock, for that zone is small or absent in the pegmatites cutting quartzite. Zone II is a normal intergrowth of the essential pegmatite minerals and is transitional with zone III in which microcline deposition, often in gigantic crystals, was dominant. Beryl and tantalite appear to have crystallized simultaneously with the large microcline, and some of the beryl crystals continued to grow into the central cavity of the pegmatite which was later filled with the quartz of zone IV.

In the lithium-bearing pegmatites, spodumene began to crystallize with the large microclines and continued into the quartz phase.

Albitization appears to have begun late in the sequence and probably was contemporaneous with the deposition of the quartz of zone IV.

The quartz of zone IV contains liquid-filled vacuoles with vapor bubbles similar to those occurring throughout the world in quartz veins of hydrothermal origin, and sulphides, although not abundant, have been found in this zone in many pegmatites. Clear quartz crystals lining the vugs of zone IV in some pegmatites show the same freqency of twinning—both Brazil and Dauphiné—that characterizes the quartz veins of Brazil. Thus, there appears to be some evidence to jus-

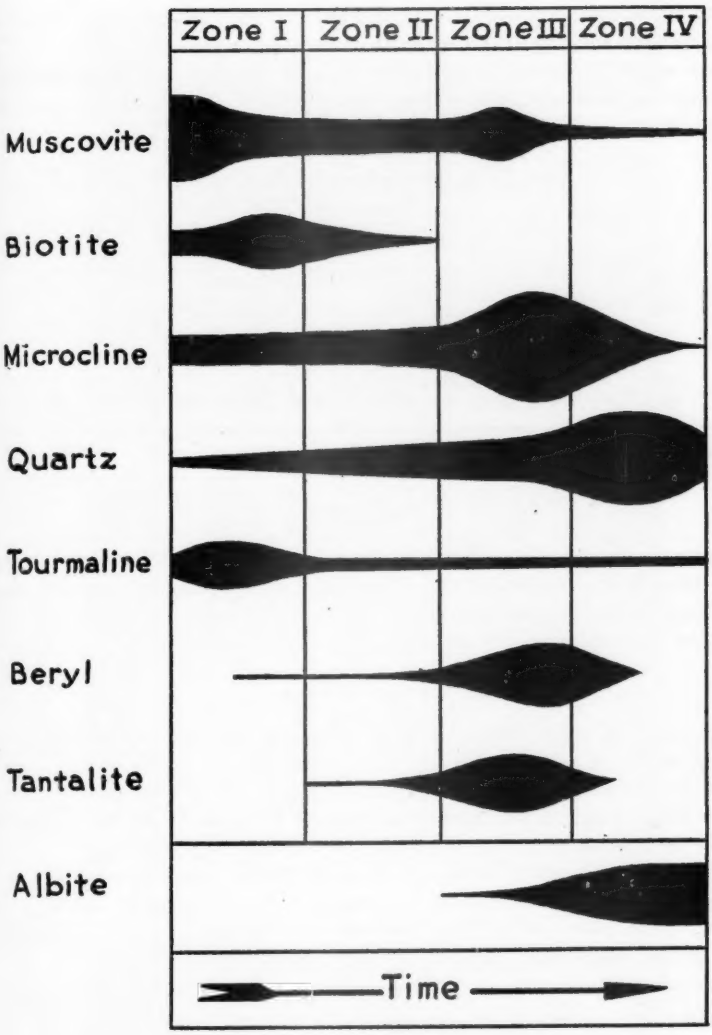

FIGURE 17.—*Paragenetic diagram*

Showing approximate order and relative rate of crystallization of the principal pegmatite minerals and their zonal distribution in the pegmatite.

tify the viewpoint that the final quartz phase of pegmatitic differentiation, such as is represented by zone IV, is a hydrothermal process wherein quartz was deposited from dilute aqueous solutions at fairly low temperatures.

In the lack of detailed mapping, we have little information about the major structural pattern of the area. Airplane photographs show the schist bending around

granite intrusions. Probably the cavities into which the pegmatites were introduced resulted from movement occasioned by granitic injection.

There appear to be many similarities between the forms of the pegmatites of Northeastern Brazil and those of Argentina (Catalano, 1940, p. 61–118) and Madagascar (Lacroix, 1922).

TABLE 5.—*Exports of pegmatite minerals from Brazil*
(Metric tons)

Year	Beryl	Tantalite	Spodumene
1938	262	38	
1939	276	59	
1940	1,472	42	
1941	1,703	94	
1942	1,634	113	
1943	1,788	198	330
Total.....	7,135	544	330

PRODUCTION

Mining of the pegmatite minerals of the region began in 1937, and, to the end of June, 1944, about 8000 metric tons of beryl, 600 tons of tantalite, and 300 tons of spodumene have been produced.

Export data are given in Table 5.

MINING METHODS

In general, the mining plan in the heterogenous pegmatites is to search for pockets of beryl and tantalite in the big feldspars of zone III. Cuts are opened on either side of the quartz core, and all of zone III is broken and searched for tantalite and beryl. In some pegmatites, where beryl extends into zone IV, it too is mined, but usually the quartz core is left in place.

Before mid 1943, all the mining in the region was by hand methods, but in the last half of that year a number of compressors were introduced by the U. S. Purchasing Commission, and air hammers were used in drilling holes for blasting in some of the larger pegmatites.

When water is available, alluvial material from the sides of the altos is washed in the type of box shown in Figure 1 of Plate 5.

DESCRIPTION OF INDIVIDUAL PEGMATITES

PICUÍ-PARELHAS AREA OF PARAÍBA AND RIO GRANDE DO NORTE

General considerations.—The 21 pegmatites from this area that are briefly described were selected to represent not only the best producing mines, but also the range of mineralogic and structural variation of the heterogeneous pegmatites of the region.

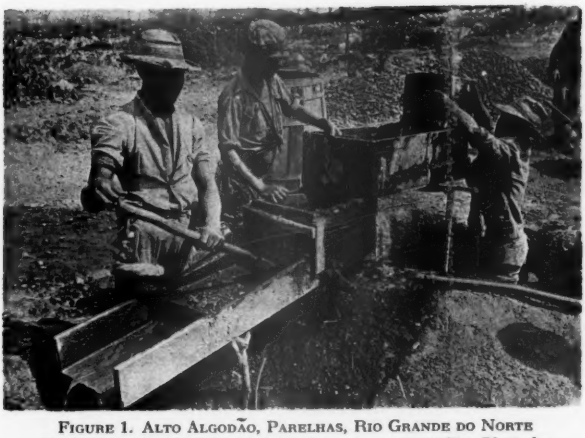

FIGURE 1. ALTO ALGODÃO, PARELHAS, RIO GRANDE DO NORTE
Washing residual gravel in a "caixa" to recover tantalite. Photo by Alan Fisher.

FIGURE 2. CLEANING TANTALITE CONCENTRATES IN "BATEIAS"
Warehouse of Silveira Brazil, Campina Grande, Paraíba. Photo by Alan Fisher.

FIGURE 3. THREE TONS OF TANTALITE
Warehouse of Silveira Brasil, Campina Grande, Paraíba. Photo by Alan Fisher.

Most were mapped with a plane table and telescopic alidade on a scale of 1 to 1000, using a contour interval of 5 meters. Maps not reproduced here are contained in the Brazilian publications (Johnston, 1945a; 1945b). The exposures in the altos did not appear to justify mapping on a larger scale in the time available. Instead, vertical sections and sketches were made of particularly good exposures. All elevations are assumed.

The following descriptions are arranged alphabetically by the name of the alto.

Algodão.—Alto Algodão is in the municipality of Parelhas, Rio Grande do Norte, about 16 km. from the city of Parelhas on the road to Barra. It is a low rounded alto situtated in the flat of the Rio Seridó.

The country rock is Seridó schist whose schistosity strikes N. and dips 30° E. The long axis of the alto is transverse to the regional structure. The outcrop of the pegmatite is 110 by 20 meters.

Zone I is well developed, zone II makes up most of the outcrop area, and zone III is small consisting of narrow bands surrounding the multiple quartz nuclei of zone IV.

All exposed contacts are nearly vertical.

Most of the tantalite obtained here has come from alluvium on the slopes of the alto. Very little mining has been done in the alto itself.

Boqueirão.—Alto Boqueirão is about 3 km. east of Parelhas, Rio Grande do Norte. It is at the crest of the northern end of the Serra dos Queimados where the Rio Seridó cuts through the range. Its elevation is about 500 meters, some 300 meters above the city of Parelhas. It is connected with the city of Parelhas by a steep road, passable only for jeeps or trucks with four wheel drives.

The wall rock of the pegmatite is a conglomerate, interbedded in the Seridó schist, containing pebbles of granite, gneiss, and quartzite. The average strike of the schistosity of the conglomerate is N. 80° W., and the average dip is 25° NE.

The outcrop dimensions of the Boqueirão pegmatite (Fig. 18) are about 240 meters in length and 25 meters in width. The dike pinches out on the west, and on the east it is cut off by a vertical cliff of the Serra.

Zone I is well developed in a few places, but generally it is absent. Zone II, which comprises roughly about half the outcrop area, contains much black tourmaline. Zone III is well developed and contains gigantic microcline crystals partially replaced by albite, and later kaolinized near the surface (Fig. 10). Zone IV consists of multiple cores of milky quartz, some of which contain vugs lined by euhedral quartz crystals (Pl. 4, fig. 1), some of which weigh over 200 kilograms.

All the exposed walls are nearly vertical.

The necessory minerals are black tourmaline; tantalite; beryl; arrojadite, which alters to yield vivianite, manganese oxides, and, possibly, rhodonite; spodumene; lepidolite; pitchblende, with its alteration products; metallic bismuth, which alters to bismutite; and chalcocite yielding copper carbonates.

This has been one of the most productive altos in the Parelhas region. Open cuts have been made along zone III and have included some of the quartz of zone IV (Fig. 18).

Damião.—Alto Damião is about 5 km. northeast of Picuí, Paraíba, on the road to Frei Martinyo. It has a low rounded outcrop approximately 120 by 70 meters.

The country rock is Seridó schist which strikes NW. and dips about 20° NE. This appears to be the bottom part of a pegmatite disk which lies on its side. The open cut on the north side exposes a window of schist which is probably the floor of the pegmatite (Figs. 19, 20). In the cut on the northwest side, the wall dips

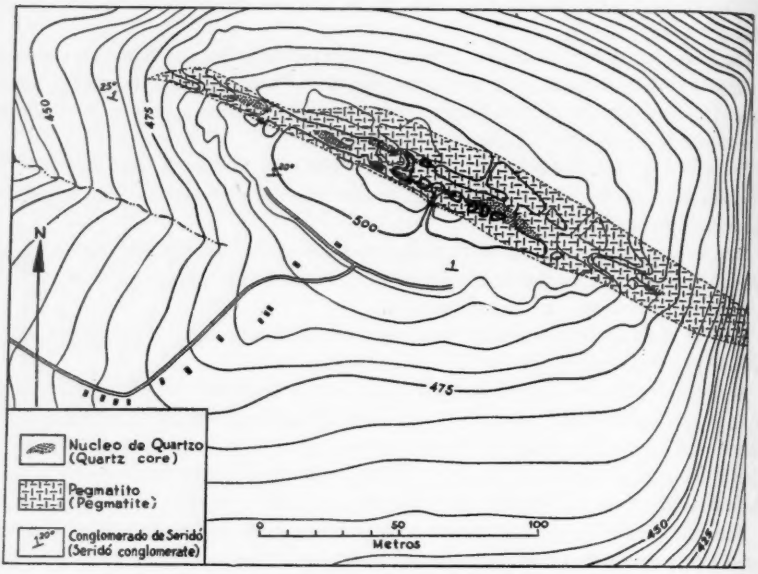

FIGURE 18.—*Sketch map of Boqueirão, Parelhas, Rio Grande do Norte*

Contour interval 5 meters. Assumed altitude

inward at 20°. These relations strongly suggest that most of the pegmatite has been removed by erosion.

Zone I, which is well developed, contains much tourmaline (Fig. 20); zone II has an average width of about 15 meters; zone III comprises most of the outcrop area; and zone IV is represented by several small quartz nuclei.

The large open cut on the south side had yielded both tantalite and beryl, and much tantalite has been recovered from the alluvium on the slopes.

Dinheiro.—Alto Dinheiro, at Carnaúba, in the municipality of Acarí, is of interest particularly because of its wall-like outcrop which rises 23 meters above the foot of the alto.

Its outcrop is about 170 meters long and 4 to 20 meters wide. The narrow northern and western part of the dike has the characteristics of a homogeneous pegmatite, but the wider eastern end is well differentiated. Zone I is only 10 to 20 cm. in width; zone II comprises most of the dike; zone III, which is narrow, surrounds the small quartz core of zone IV.

This dike has produced a little tantalite and beryl. A few specimens of a brilliant black tantalate of the rare earths, resembling samarskite, have been found here.

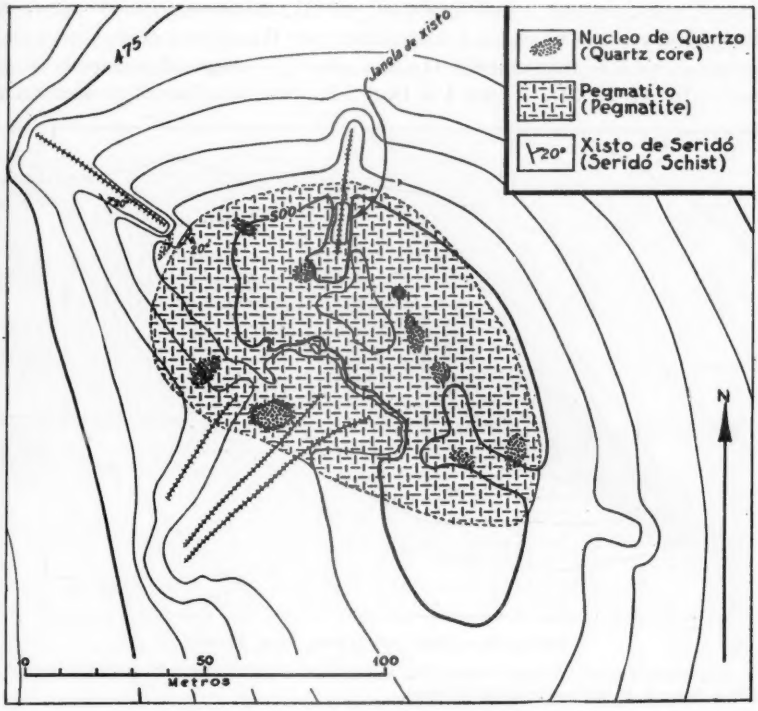

FIGURE 19.—*Sketch map of Damião, Picuí, Paraíba*

Contour interval 5 meters. Assumed altitude

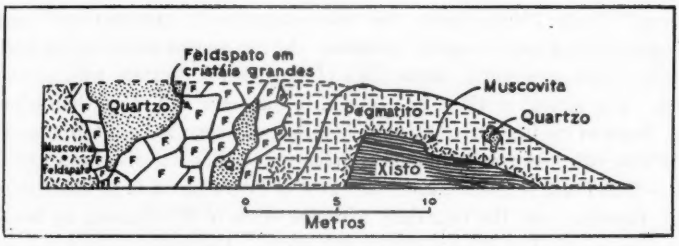

FIGURE 20.—*Sketch section of Damião, Picuí, Paraíba*

Showing the schist floor of the pegmatite

Feio.—Alto Feio, at the town of Pedra Lavrada, Paraíba, is the largest heterogeneous pegmatite in the region. Its outcrop dimensions are 500 meters in length and 100 meters in maximum width (Fig. 21). The pegmatite is located on a contact between the Seridó schist and a gray granite.

Zone I, where exposed, is well developed; zone II, which comprises about half the outcrop area, contains much black tourmaline; zone III contains microcline crystals weighing as much as 100 tons (Fig. 11); and zone IV is composed principally of rose quartz (Figs. 11, 22, 23). Figure 1 of Plate 3 is of the inner face of an open cut on

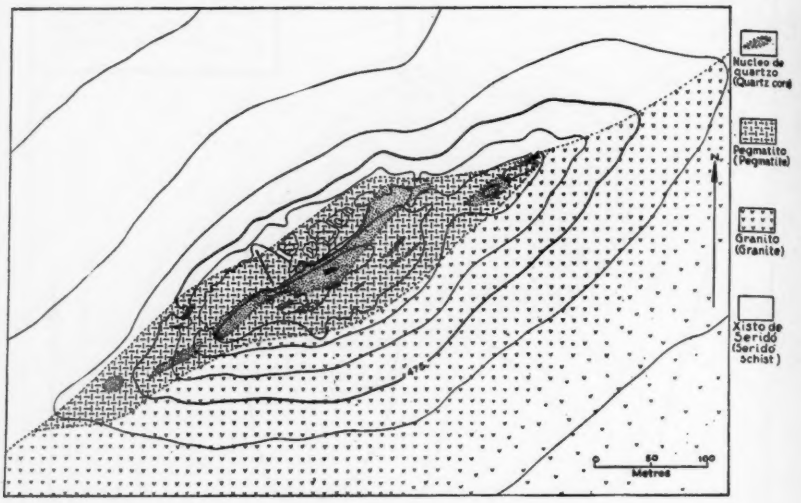

FIGURE 21.—*Sketch map of Feio, Picuí, Paraíba*

Contour interval 5 meters. Assumed altitude. This map was made in July 1922 by Sandoval Carneiro de Almeida and W. D. Johnston, Jr., and is without vertical control.

the south side which parallels the long axis of the alto. It shows the large crystals of microcline and quartz that are characteristic of the contact between zones III and IV.

Between 1938 and 1943 inclusive, this mine is reported to have produced about 700 metric tons of beryl and 4 tons of tantalite. In the quartz cores on the north side of the alto, there are many impressions of large beryl crystals which have been removed. The largest of these was 60 cm. in diameter and more than a meter in length. Some of the beryl from this alto is sufficiently clear to be cut for aquamarine, but it is very pale. A small amount of green tourmaline has also been found.

Forte.—Alto Forte is about 7 km. northwest of Pedra Lavrada in the municipality of Picuí, Paraíba, near the boundary with the state of Rio Grande do Norte. Its outcrop dimensions (Fig. 24) are 180 by 30 meters. The walls exposed dip outward, suggesting that the surface cuts this pegmatite near the top. This impression is strengthened by the irregular inclusions of schist within the alto.

Zone I is well developed and has yielded a small quantity of commercial mica; zone II is relatively small; zone III makes up most of the outcrop area; and zone IV is represented by two small quartz nuclei.

This alto is said to have produced about 3 metric tons of beryl and 1.5 tons of tantalite up to February 1, 1944.

Gamenho.—Alto Gamenho is about 30 km. southeast of Parelhas, near Barra, Rio Grande do Norte. The country rock is Seridó schist striking to the northeast and dipping vertically. The long axis of the pegmatite makes an angle of about 30° with the regional schistosity.

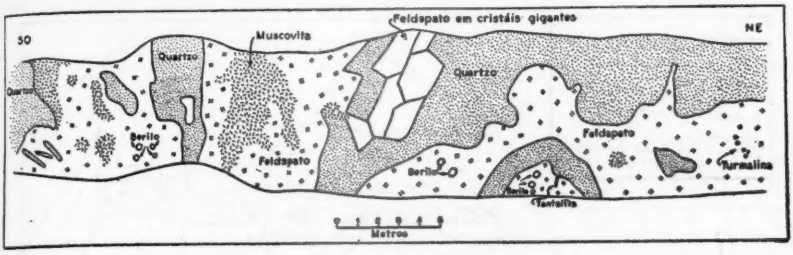

FIGURE 22.—*Sketch section of Feio, Picuí, Paraíba*

The section is parallel with the long axis of the pegmatite and passes through the interfingered contact between zones III and IV.

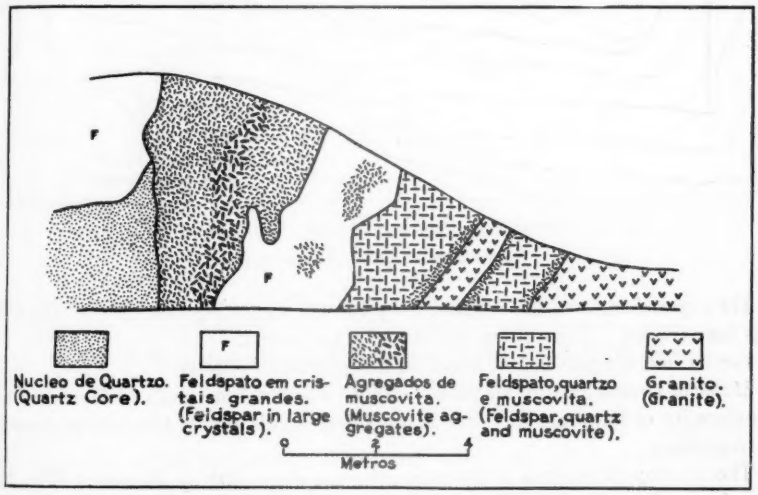

FIGURE 23.—*Sketch section across the southeast half of Feio, Picuí, Paraíba*

Showing the muscovite band along the granite walls

The outcrop dimensions of the pegmatite are 165 by 30 meters. Most of the exposed walls dip inward, suggesting that the surface cuts this pegmatite below its center and that most of the original body has been removed by erosion.

Zone I is narrow, but well developed; zone II makes up about half the outcrop area; zone III is well developed; and zone IV is represented by a small nucleus of quartz at the northern end.

This alto has produced a fair quantity of tantalite but very little beryl.

Garrote.—Alto Garrote No. 1 (Pl. 2, fig. 1) is near the road from Picuí to Carnaúba,

in the municipality of Acarí, Rio Grande do Norte. This is a small alto 80 by 15 meters in outcrop dimensions whose long axis is nearly at right angles with the structure of the Seridó schist which forms the walls. There is a smaller, parallel homogeneous dike about 80 meters to the north.

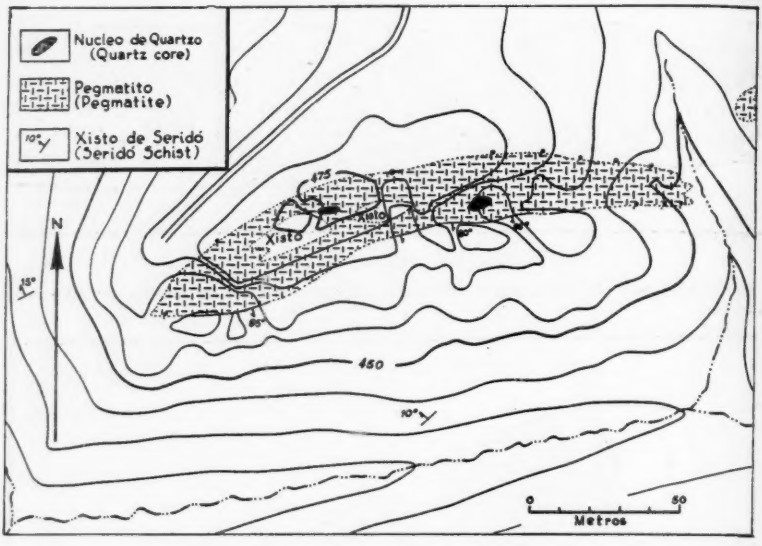

FIGURE 24.—*Sketch map of Forte, Picuí, Paraíba*

Contour interval 5 meters. Assumed altitude

The exposed walls of the pegmatite dip inward suggesting that most of the body has been eroded. The western end is cut by two faults.

For its size, the production record of this pegmatite is good.

Malhada Grande.—Alto Malhada Grande, about 6 km. south of Barra, in the municpality of Parelhas, Rio Grande do Norte, stands almost 100 meters above its surroundings.

The outcrop dimensions of the pegmatite are about 100 by 20 meters (Fig. 25). The long axis makes an angle of 60° with the regional schistosity. The exposed walls dip to the south, suggesting that the pegmatite disk is inclined southward at an angle of about 60°.

Zone I is generally narrow (Fig. 26); zone II is narrow and irregular; zone III is well developed; and zone IV is large.

A short tunnel at the eastern end cut highly albitized feldspars containing crystals a few millimeters in diameter of disseminated tantalite. At the western end of the quartz core coarse tantalite was found. A little cassiterite occurs in the feldspars of zone III near the center of the pegmatite.

This alto has had a good production record for tantalite but has yielded very little beryl.

Mamões.—Alto Mamões is on the principal highway from Equador to Parelhas, about 5 km. north of Equador in the municipality of Parelhas, Rio Grande do Norte. It is a narrow vertical dike about 450 meters long and 30 meters in maximum width (Fig. 27). Where exposed, the walls are vertical. The country rock is quartzite interbedded in the Seridó schist, which strikes northeast and dips northwest.

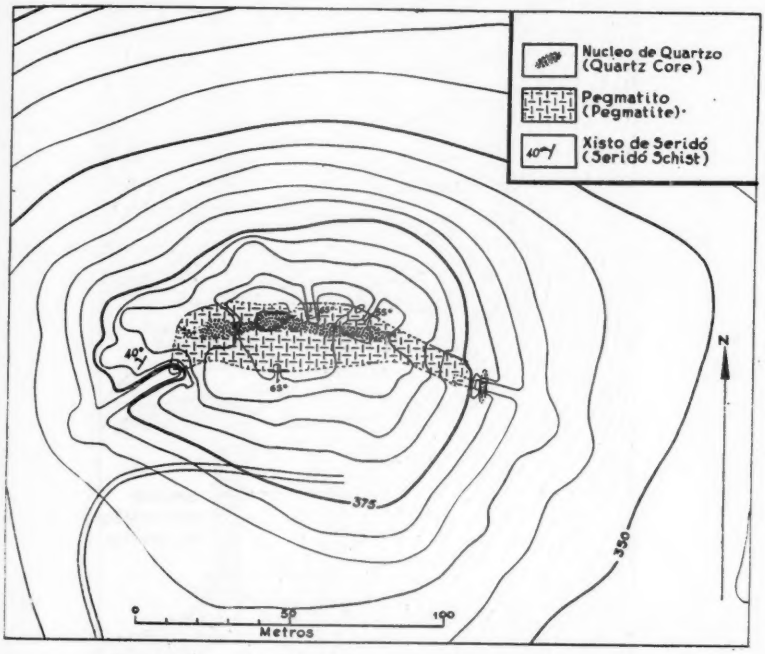

FIGURE 25.—*Sketch map of Malhada Grande, Parelhas, Rio Grande do Norte*
Contour interval 5 meters. Assumed altitude

Zone I is poorly developed; zone II, which makes up most of the western fork of the pegmatite, is well developed and contains much tourmaline; zone III occupies the center of the eastern fork except for the isolated quartz nuclei of zone IV. This pegmatite appears to be transitional with the homogeneous dikes in that its form is more linear, and, in general, the feldspars of zone III are not so large as is usually the case in the lenticular dikes.

Mamões has a good production record for both tantalite and beryl. One beryl crystal weighed about 2.5 metric tons. A small amount of simpsonite has been found here.

The neighboring Alto Gis, situated on a steep hillside about 1 kilometer north of Manões, is also in quartzite. It has yielded simpsonite, manganotantalite, and microlite, as well as tantalates and niobates of the rare earths. This alto has been described in some detail by Pough (1945b).

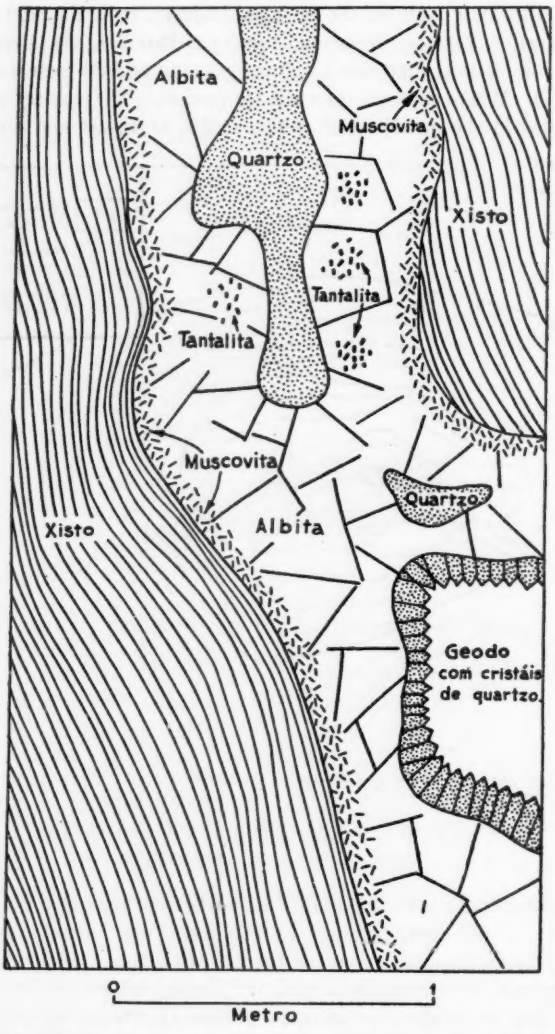

FIGURE 26.—*Sketch of the face of the east tunnel, Malhada Grande, Parelhas, Rio Grande do Norte*

Showing tantalite disseminated in albite that has replaced microcline

Marimbondo.—Alto Marimbondo is about 3 km. south of Carnaúba, in the municipality of Acarí, Rio Grande do Norte.

It is on the shoulder of a serra whose eastern slope, below the outcrop of the pegmatite, has been the site of placer mining for tantalite and cassiterite.

Zone I attains a maximum width of 1 meter and contains much biotite; zone II is relatively narrow and has some graphic granite; zone III is well developed and is

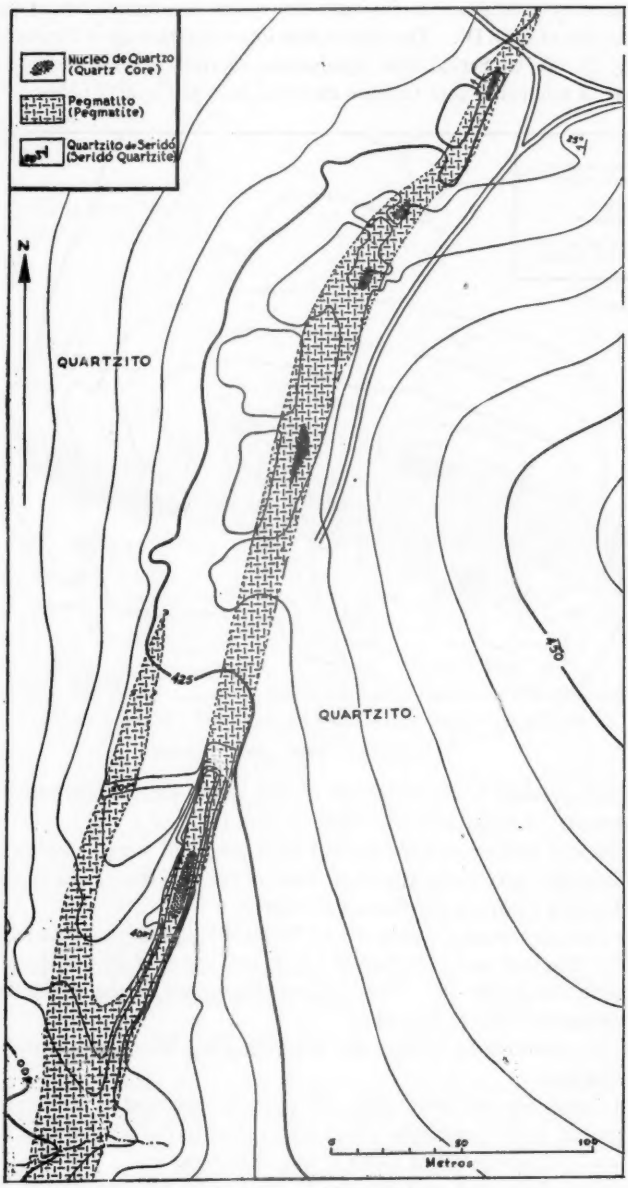

FIGURE 27.—*Sketch map of Mamões, Parelhas, Rio Grande do Norte*

Contour interval 5 meters. Assumed altitude

characterized by spodumene on its inner side which continues into the outer rim of the quartz core of zone IV. The spodumene forms crystals up to 2 meters in length (Pl. 4, fig. 2). As at Seridózinho, spodumene crystallization appears to have outlasted that of microcline and to have extended into the quartz phase. Cassiterite

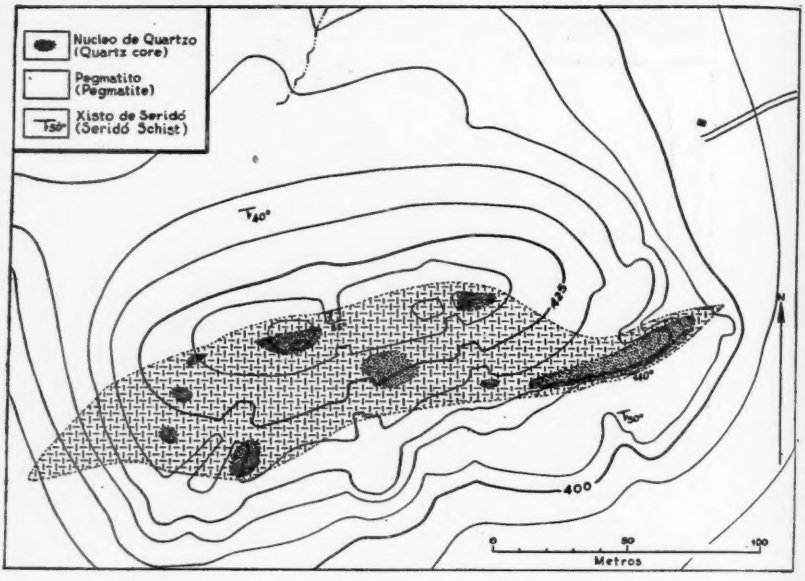

FIGURE 28.—*Sketch map of Pedra Branca, Acarí, Rio Grande do Norte*

Contour interval 5 meters. Assumed altitude

forms minute crystals in the muscovite of zone I, and some occurs within the spodumene crystals. Arrojadite is abundant in zone III.

This alto was first worked for tin but later produced some tantalite.

Pedra Branca.—Alto Pedra Branca is south of the road from Picuí to Carnaúba, in the municipality of Acarí, Rio Grande do Norte.

It is a conspicuous alto, rising about 50 meters above its surroundings (Pl. 1, figs. 2, 3). The wall rocks are Seridó schist, and the long axis of the pegmatite is parallel with the schistosity. The outcrop dimensions of the pegmatite (fig. 28) are approximately 280 by 50 meters.

All exposed contacts dip to the south suggesting that the pegmatite disk is inclined in that direction.

All four zones are well developed. Of particular interest is the quartz body on the eastern end of the pegmatite which lies so close to the schist contact that zones I to III are compressed into a width of only 8 meters.

At the time of my visit on February 22, 1944, work has just started on this alto, and only a small amount of tantalite and beryl had been produced. One specimen of interest showed beryl with small included crystals of tantalite.

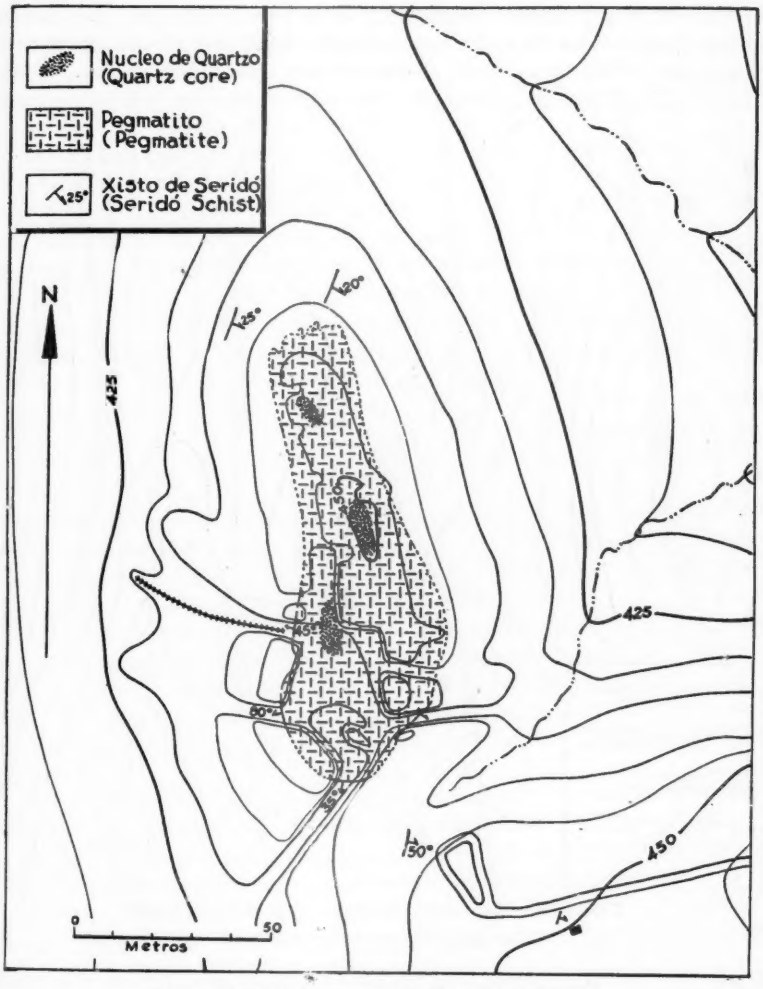

FIGURE 29.—*Sketch map of Piaba No. 1, Picuí, Paraíba*

Contour interval 5 meters. Assumed altitude

Piaba No. 1.—Alto Piaba No. 1 (Fig. 29; Pl. 2, fig. 2) is northwest of Pedra Lavrada, municipality of Picuí, Paraíba, near the boundary of the state of Rio Grande do Norte. The wall rocks are Seridó schist dipping 20°–25° E., and the long axis of the pegmatite makes a low angle with the strike of the schistosity.

The outcrop dimensions of the pegmatite are 110 by 40 meters. All exposed walls dip outward, suggesting that only the top of the pegmatite has been uncovered by erosion. All zones are well developed and characteristic. Of interest is the unusual

development of long bladed crystals of biotite in zone II (Pl. 4, fig. 3). Tantalite has been found in zone III within large microcline crystals, at the microcline-quartz contact, and within intergrowths of rosetted muscovite and microcline. A small

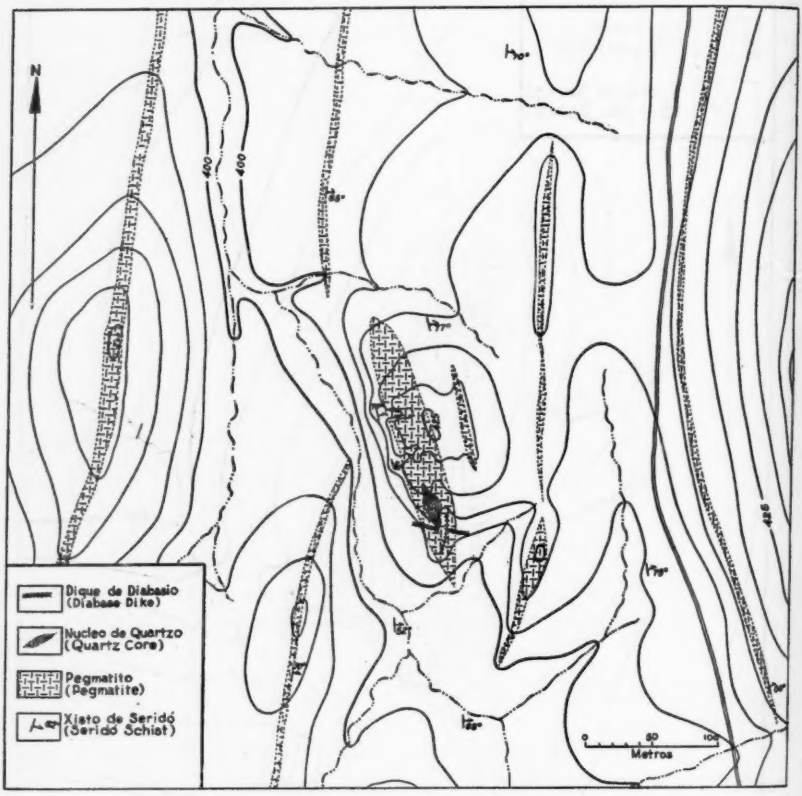

FIGURE 30.—*Sketch map of the Quixabeira area, Picuí, Paraíba*

Contour interval 5 meters. Assumed altitude

amount has also been reported from the inner margin of zone II in mixed pegmatite. The largest pocket of tantalite, which contained more than 1 ton of that mineral, was in large microcline crystals at the quartz contact. Some arrojadite and spodumene also occur.

This is one of the outstanding mines of the district. In 1942 and 1943 it produced a total of about 11 metric tons of tantalite and 30 tons of beryl.

Quixabeira.—Alto Quixabeira is north of Picuí and east of the main road to Frei Martinho in the municipality of Picuí, Paraíba. There are many homogeneous dikes in the region which strike northward in conformity with the structure of the Seridó schist (Fig. 30).

Quixabeira has an outcrop length of about 220 meters and a maximum width of

about 30 meters. All zones are developed and characteristic. A narrow dike of diabase cuts the southern end of the pegmatite.

Production of beryl and tantalite has been small.

Redondo.—Alto Redondo is near Barra in the municipality of Parelhas, Rio Grande do Norte.

It is a low small alto with outcrop dimensions of about 80 by 30 meters. The exposed walls dip outward indicating that only the top of the pegmatite has been removed by erosion. All four zones are present, but zone IV is represented by only a single small outcrop of quartz. This alto has produced principally beryl.

Santo Antonio.—Alto Santo Antonio is in the municipality of Lages, approximately 36 km. north of São Tomé. Its outcrop dimensions are about 105 by 40 meters, but, because of poor exposures, its limits are not certain. The principal exposures are in the workings at its southern end. Zone I is 10 to 20 cm. wide; zone II is relatively narrow; and most of the open cut is in zones III and IV.

Specimens of both beryl and tourmaline from this alto have been fractured and recemented by quartz. Production from the alto itself has not been large, but the alluvium on the lower slope is said to have yielded about 2 tons of tantalite and 3 tons of beryl up to the end of June 1944.

Seridózinho.—Alto Seridózinho is 9 km. north of the city of Joazeiro, Paraíba. It is located on the Borborema Plateau at an approximate elevation of 500 meters.

The accompanying map (Fig. 31) is from a private report by Dr. Sandoval Carneiro de Almeida, who kindly made it available to me.

The dimensions of the pegmatite outcrop are about 300 by 40 meters. All four zones are well developed. As at Marimbondo, spodumene in crystals up to 2 meters in length occur both in the feldspars of zone III and the peripheral part of the quartz of zone IV, indicating that spodumene crystallization extended into the quartz phase. Cassiterite occurs in zone I interleaved in the muscovite books. Beryl and tantalite are in zone III.

Figure 31 shows two faults which cut off the pegmatite. There are other smaller faults, however, along which the pegmatite is not displaced.

To the end of November 1943 this mine had produced about 12 metric tons of tantalite, 42 tons of cassiterite, 65 tons of beryl, and 325 tons of spodumene.

Tobôa.—Alto Tabôa is south of the road from Picuí in Carnaúba, in the municipality of Acarí. It lies on the slope of an outlying remnant of the Borborema peneplane (Fig. 32).

The outcrop dimensions of the pegmatite are approximately 220 by 35 meters. Its long axis conforms with the schistosity of the wall rocks.

All zones are well developed and characteristic (Fig. 9).

This has been one of the most productive altos in the region. Between 1938 and 1943, inclusive, it yielded 11 metric tons of tantalite and 285 tons of beryl.

Tanquinhos.—Alto Tanquinhos is west of the highway from Picuí to Nova Palmeira, in the municipality of Picuí, Paraíba. With the exception of Feio, it is the largest alto in the region and has been one of the most productive. The outcrop dimensions are approximately 400 by 100 meters (Fig. 33). Its long axis parallels the strike of the Seridó schist. The walls dip inward, and the width of the pegmatite

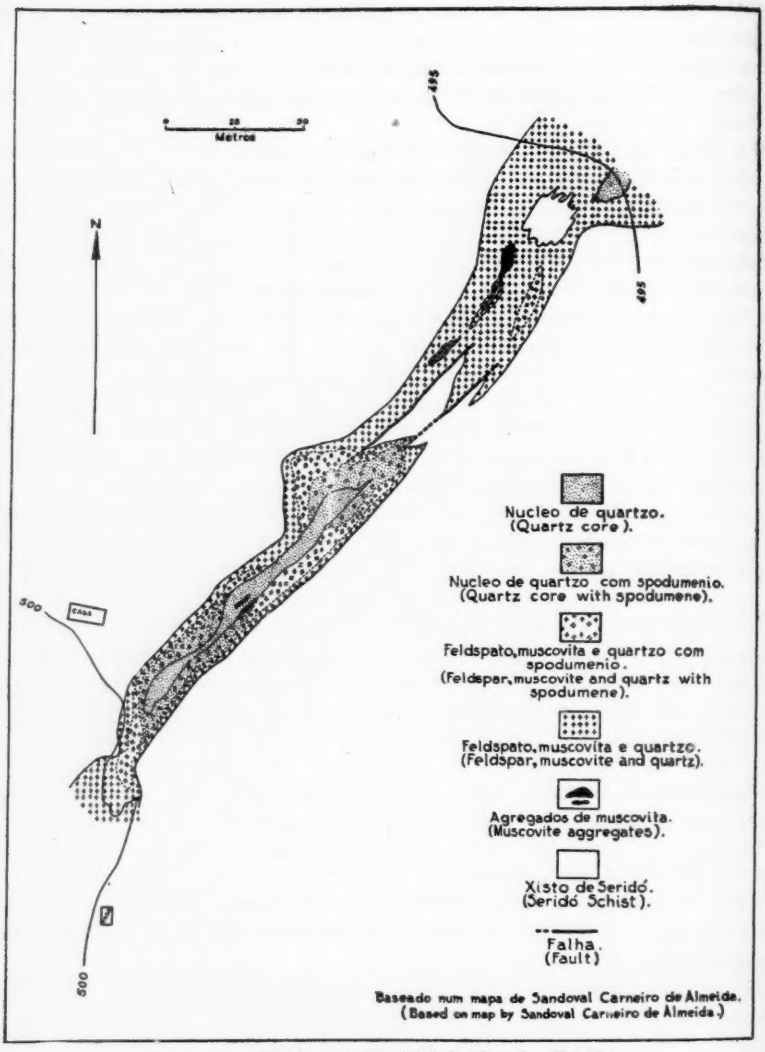

FIGURE 31.—*Sketch map of Seridózinho, Joazeiro, Paraíba*

Contour interval 5 meters. Assumed altitude

at the tunnel level is about 3 meters (Fig. 34). Pobably the pegmatite disk is horizontal, and the upper half of it has been removed by erosion.

Zone I is well developed, and, some years ago, the long open cut at the north end of the western side of the pegmatite was opened to mine mica. Zone II, which

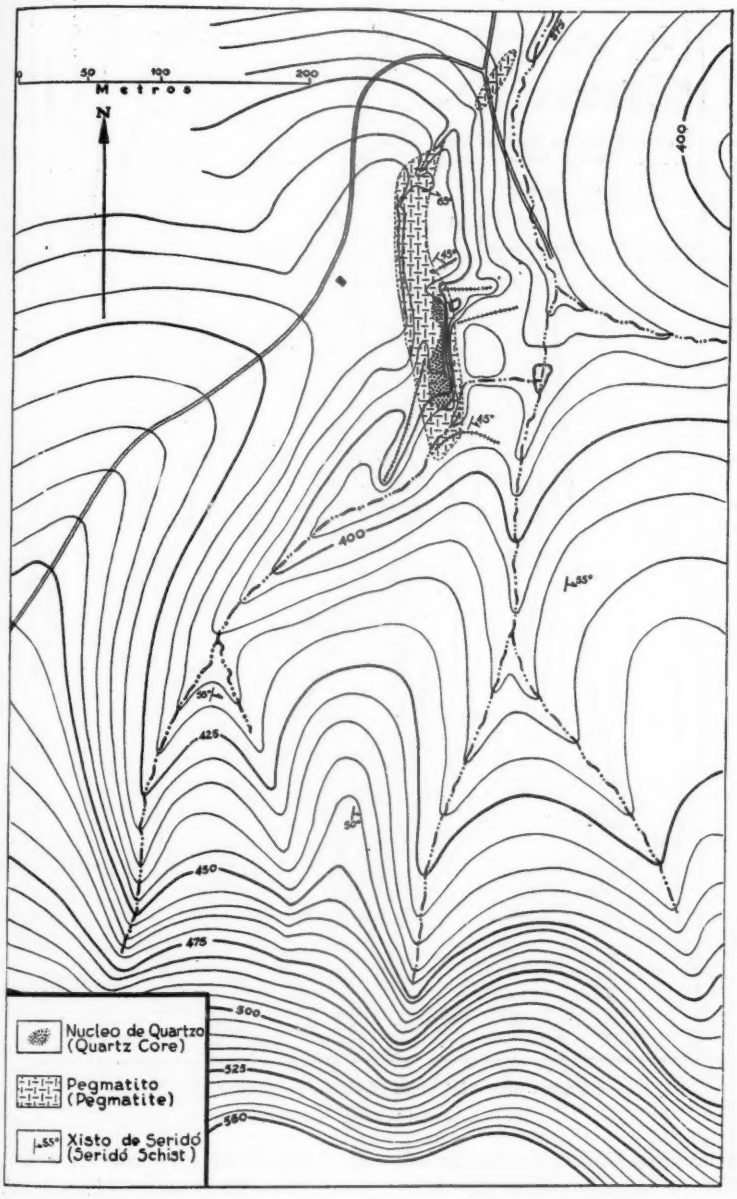

FIGURE 32.—*Sketch map of the Taboa area, Acarí, Rio Grande do Norte*

Showing remnant of the Borborema peneplain at elevation 550. Contour interval 5 meters. Assumed altitude

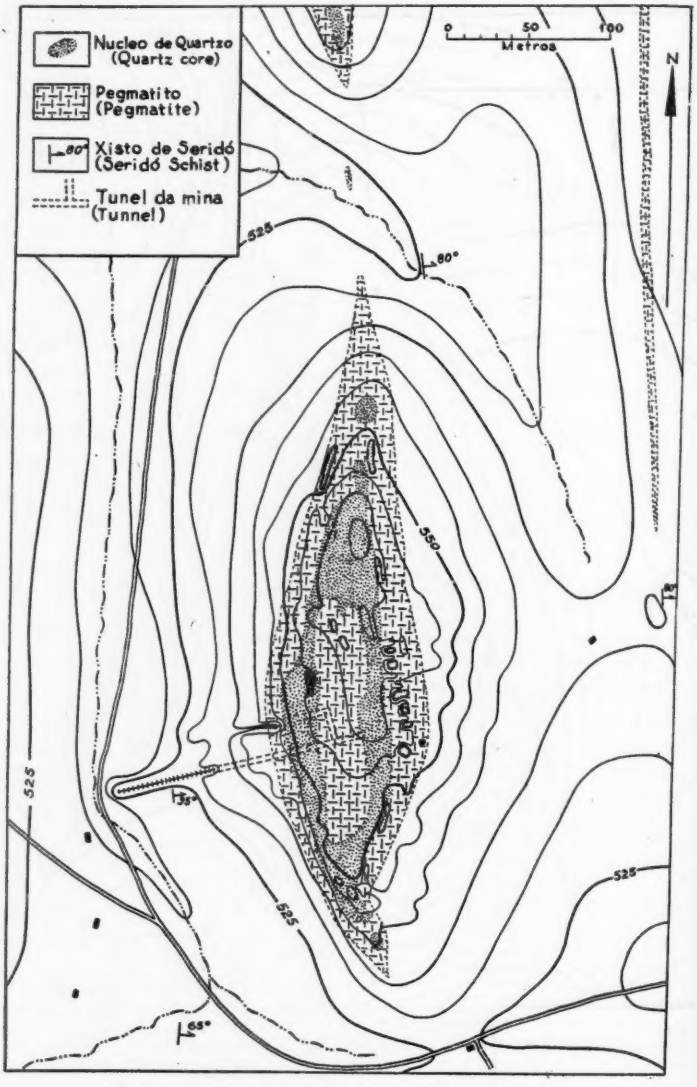

FIGURE 33.—*Sketch map of Tanquinhos, Picuí, Paraíba*

Contour interval 5 meters. Assumed altitude

contains some biotite, is characteristic and is transitional into zone III which has yielded the tantalite and beryl. A large area of zone III is enclosed in zone IV.

Figure 14 is a careful sketch made in July 1943 of a face in a deep cut on the east side of the pegmatite, parallel with its long axis. It showed more beryl and tantalite

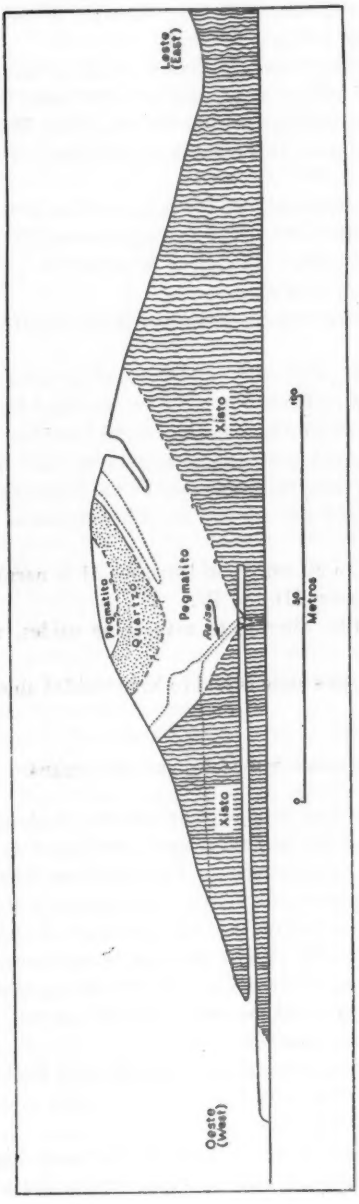

FIGURE 34.—*Sketch section of Tanquinhos, Picuí, Paraíba*
Section transverse to the long axis of the pegmatite outcrop

than I had seen at any other mine. The area sketched is said to have yielded more than 1 ton of tantalite and 100 tons of beryl.

The largest single crystal of tantalite found is said to have weighed about 500 kilograms, and the largest pocket of tantalite contained more than 2 tons.

Other minerals found in this alto are garnet, arrojadite, bismuth, and bismutite.

From 1938 to 1943, inclusive, this mine produced about 15 tons of tantalite and 834 tons of beryl.

Tibirí.—Alto Tibirí is on the road from Pedra Lavrada to Barra, in the municipality of Parelhas, Rio Grande do Norte. The outcrop area of the pegmatite is approximately 150 by 30 meters. The wall rock is Seridó schist lying horizontally. All zones are present and characteristic.

A homogeneous pegmatite striking north and dipping east is about 40 meters to the west.

Tibirí is one of the most productive pegmatites of the area. Between 1938 and 1943 it is said to have produced about 9 tons of tantalite and 130 tons of beryl.

Urubú.—Alto Urubú is about 3 km. north of Picuí, Paraíba. Its long axis strikes northward in conformity with the regional schistosity, and its exposed walls dip steeply to the east. The outcrop dimensions of the pegmatite are approximately 135 by 18 meters. To the south are two small homogeneous pegmatites with the same strike.

Zone I ranges from 10 to 50 cm. in width; zone II is narrow; and most of the pegmatite is made up of zones III and IV.

Arrojadite and spessartite, altering to manganese oxides, are present in small amounts.

Between 1938 and 1943, this mine is said to have yielded about 8 tons of tantalite and 120 tons of beryl.

QUIXERAMOBIM-CACHOEIRA AREA, CEARÁ

General considerations.—More than 50 pegmatites in the Quixeramobim-Cachoeira area have been worked to some degree for beryl, amblygonite, and tantalite. Ten pegmatites in that area are described here. They are characteristic of the pegmatites that have proven to be the most productive. All elevations are assumed.

The area (Fig. 3) includes parts of the municipalities of Quixeramobim and Cachoeira. It is a region of low relief wherein the most conspicuous topographic elements are monadnocks of granitized schist. The country rock is a quartz-mica schist that, in places, has been granitized and assumes a gneissic aspect. Intercalated in the schist are beds of quartzite and marble.

The pegmatites of the area, unlike those in Paraíba and Rio Grande do Norte, are without topographic expression, save for a residual rubble of quartz and pegmatite fragments that mark their outcrops.

Belém.—The Belém mine is on the fazenda of Raimundo Nogueira Pinheiro and André Leonidas Pinheiro, about 8 km., by road, west of the town of Cachoeira in the municipality of Cachoeira. It is a small pegmatite characterized by its prominent quartz core.

The dike outcrops on the end of a small ridge composed of fine-grained granite gneiss. Two sections of the dike are well exposed, the eastern section for a strike length of about 20 meters and the western section for a strike length of about 25 meters. Between these two sections, the dike is marked by residual quartz on the surface. There is much residual quartz also on the western slope of the ridge.

The most conspicuous feature of this dike is a continuous quartz core 2 to 2.5 meters wide, flanked on either side by 1 to 1.5 meters of pegmatite consisting essentially of zones II and I. No large feldspars are present.

This mine was originally opened for mica contained in zone I, but work was continued in search of beryl, tantalite, and amblygonite contained in zone II at the contact with the quartz core. As all the work was done by garimpeiros or itinerant miners, the production is not known. A few kilograms of amblygonite remained at the mine.

Belo Horizonte No. 2.—Belo Horizonte No. 2 is about 13 km., by road, southwest of the town of Cachoeira in the municipality of that name, on the farm Belo Horizonte belonging to Gustavo Pinheiro Landum. The pegmatite outcrops on the north side of a small hill. There is no topographic expression of the dike itself.

The pegmatite is about 70 meters long with an average width of 5 meters. It is very poorly zoned. Zone I is narrow and irregularly developed, zone II makes up most of the dike, and zones III and IV are represented by narrow shells of coarse feldspar surrounding the two quartz nuclei. Much of the original microcline has been replaced by cleavelandite. The dike has yielded a small amount of beryl and amblygonite from the open cut shown in Figure 4 of Plate 2.

Belo Horizonte No. 1 and No. 3, on the same farm, are smaller dikes which have produced less than Belo Horizonte No. 2. Belo Horizonte No. 3 has yielded a few fairly well formed amblygonite crystals.

Bom Jesus de Francisco Carneiro Machado.—This mine is 1 kilometer north of the main Cachoeira-Berilândia road about 22 km. north of Cachoeira in the municipality of that name. It is on the fazenda Bom Jesus belonging to Francisco Carneiro Machado and has been worked by the Sociedade de Minérios Ltda.

The country rock is a quartz-hornblende-biotite schist. The pegmatite is about 140 meters long and has a maximum width of 15 meters. Where exposed, the walls dip to the north. The pegmatite, in general, is poorly zoned. Zone I is narrow and is not continuous along the whole margin of the dike. Zone II, which makes up most of the pegmatite, is a medium-grained mixture of quartz, albitized microcline, and muscovite which contains much black tourmaline. Zone III is represented by large microcline crystals in the center of the western end of the pegmatite and by shells around the quartz nuclei of zone IV. This dike appears to have a more complex history than most, for a narrow band of muscovite-rich pegmatite crosscuts the mixed pegmatite of zone III.

Amblygonite was obtained from the western end, and beryl from the eastern end of the dike. Both were most abundant at the transition between zones II and III. A few kilograms of tantalite have also been found.

Grossos No. 2.—Grossos No. 2 is about 3 km. southwest of the road from Berilândia to Cachoeira on the fazenda Grossos belonging to Pedro Filomeno Gomes & Cia.

The pegmatite is about 70 meters long and 5 meters wide enclosed in muscovite schist. The dike is essentially homogeneous, showing less zoning than do any of the other beryl-producing pegmatites in the area. It consists wholly of a coarse intergrowth of muscovite, albitized microcline, and quartz of the mineralogic type of zone III. Beryl in crystals generally less than 1 kilograms in weight appears to be distributed fairly uniformly throughout the dike. Some small fragments of a red earthy mineral probably were derived from the deomposition of a phosphate mineral similar to arrojadite. Up to mid September, 1944, this pegmatite had produced about 25 tons of beryl.

Grossos No. 1, which is near by, is composed mainly of the high muscovite pegmatite of zone I. It is originally worked for mica but has produced some beryl.

Lapinha.—Lapinha is in the municipality of Cachoeira about 10 km., by road, northwest of the town of Cachoeira, on the fazenda Lapinha belonging to J. A. Pinheiro Loudim.

The pegmatite is about 70 meters long and 15 meters in maximum width. The country rock is a quartz-biotite-hornblende schist, dipping to the northwest. Zones I and II are well developed but small, and most of the pegmatite consists of large crystals of albitized microcline of zone III. Zone IV is represented by two small quartz nuclei. The open cut on the western end of the pegmatite was not productive, but the cut on the eastern end has yielded beryl, amblygonite, and some tantalite of good grade. One tantalite pocket found in early September 1944 contained about 50 kilograms of that mineral.

Logradouro.—Logradouro, in the municipality of Cachoeira, is about 12 km., by road, west of the town of Cachoeira in the fazenda Logradouro belonging to Esperidião Paes de Lima. It is worked by Filemon Benavides de Magalhães.

The dike is about 200 meters long and 2 to 4 meters wide. The wall rock is granitized schist. Most of the dike is composed of a coarse-grained mixture of quartz, muscovite, and feldspar, of zone II. Zone I is narrow and irregular, and zone III is represented by a few pockets of big feldspar crystals. It has yielded beryl and amblygonite from zone II on the peripheries of the scattered pockets of large feldspars.

Logradouro No. 2 is a small irregular dike with zones III and IV well developed. It has yielded some tantalite.

Olho d'Agua.—Olho d'Agua is about 10 km. north of Berilândia in the municipality of Quixeramobim. It is on the fazenda Olho d'Agua belonging to José Florêncio do Nascimento and is worked by the Sociedade de Minérios Ltda.

The pegmatite is in two parts, which are not connected on the surface. The northern pegmatite is about 75 by 15 meters in outcrop area, and the southern pegmatite is about 70 meters long and 5 meters wide. The country rock is muscovite schist. A recently built reservoir has flooded some of the workings. The dike is fairly well zoned. In the southern pegmatite, zone I has a maximum width of 1 meter along the east wall and 10 cm. on the west wall; zone II is well developed; zone III is small; and zone IV is represented by two small quartz nuclei on the west or footwall of the dike. In the northern pegmatite, all zones are present.

This pegmatite is said to have produced more than 50 tons of beryl, much of which came from zone I on the east wall of the southern pegmatite.

Poço dos Cavalos.—Poço dos Cavalos (Fig. 35) is about 14 km. southeast of Berilândia in the municipality of Cachoeira. It is worked by Dr. Estevam Marinho.

This pegmatite has had a varied history. Originally worked for mica, it later was prospected for quartz and during the past 2 years it has been worked for precious garnet.

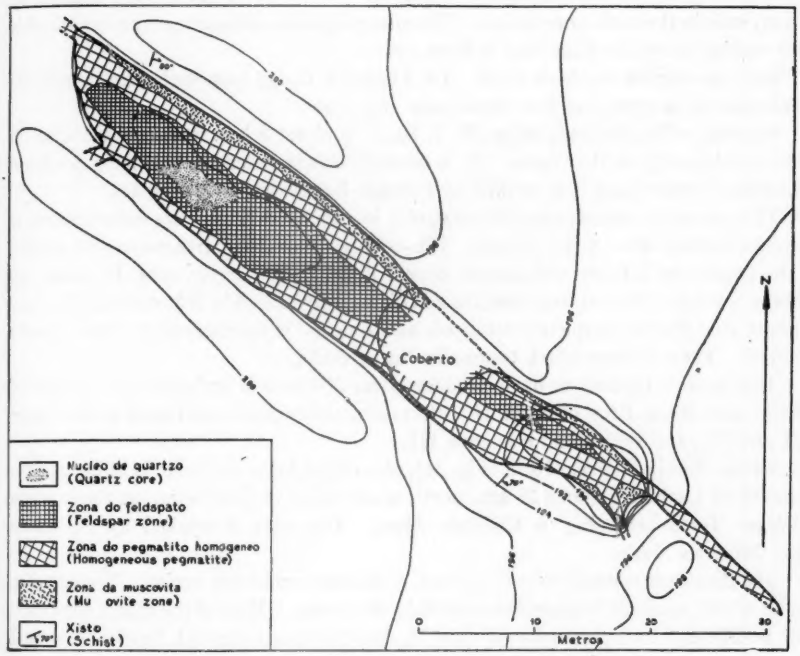

FIGURE 35.—*Sketch map of Poço dos Cavalos, Cachoeira, Ceará*

Contour interval 2 meters. Assumed altitude

The outcrop area of the pegmatite is approximately 50 meters long and 10 meters wide. The country rock is biotite schist.

This pegmatite is the most distinctly zoned dike observed. All four zones are well developed (Fig. 35). Zone I is most conspicuous on the northeast wall of the dike where it formerly was worked for mica. Zone II makes up less than half the outcrop area; zone III is large, and zone IV is represented by several nuclei of milky white quartz.

The minerals present are quartz, muscovite, microcline, cleavelandite, black tourmaline, beryl, garnet, and topaz.

The original feldspar was microcline, but most of it has been replaced by cleavelandite. A few specimens of what appeared to be fresh microcline, upon examination in thin section, were found to be half replaced by albite.

In addition to the milky quartz of the core, there are a few vugs lined by clear

quartz filled with crystals of black tourmaline. These tourmaline crystals, which range in size from needles to pencils, have no systematic orientation within the quartz crystals. Tourmaline crystals also occur in feldspar that is in contact with the clear quartz.

Garnet occurs as dark-red crystals, ranging in weight from less than a gram to over a kilogram, in both feldspar and quartz. Many of the garnets are aggregates of crystals in the same orientation. The mineral gives a deep-red gem, more suitable for cutting in smaller sizes than in large stones.

Beryl production has been small. Dr. Frederick Pough (personal correspondence) has reported a crystal of blue topaz from this mine.

Soledade.—The Soledade mine (Pl. 2, fig. 3) is about 8 km. west of Cachoeira on the municipality of that name. It is on the fazenda Soledade belonging to Anna Lucinda Pinheiro and it is worked by Filemon Benavides de Magalhães.

The pegmatite outcrops on the crest of a low rounded ridge. Its outcrop area is approximately 100 by 10 meters. The country rock is quartz-muscovite schist. The pegmatite is fairly well zoned. Zone I is generally narrow, zone II makes up about a third of the outcrop area, zone III is well developed in the center of the dike where it is almost completely albitized, and zone IV is represented by three quartz nuclei. There is some black tourmaline in this dike.

This mine is reputed to have produced over 200 tons of amblygonite, 10 tons of beryl, and about 1 ton of tantalite. Beryl and amblygonite are found in both zone II and III, and the tantalite in zone III.

Várzea Torta.—Várzea Torta (Fig. 36), also called Mina do Povo, is in the municipality of Cachoeira about 18 km. north of the town of Cachoeira, on the fazenda Várzea Torta belonging to Clarindo Alves. The mine is worked by Sociedade de Minérios Ltda.

The dike caps a small ridge composed of biotite-hornblende schist. The outcrop area of the pegmatite is approximately 90 by 30 meters. Most of the dike is composed of undifferentiated pegmatite of zone II, but the muscovite-rich border of zone I is well developed (Pl 3, fig. 3).

This mine is said to have produced about 180 tons of beryl, all from zone I. No amblygonite or beryl has been found.

Other mines in the Quixeramobim-Cachoeira area.—Of some mineralogical interest are two small pegmatites, Bolinha and Nova Bolinha, in the municipality of Quixeramobim, approximately 15 km., by road, north of Berilândia.

Bolinha has yielded some clear quartz, most of which is badly twinned, with both green and pink tourmaline. Most of the tourmaline crystals have pink centers and green margins. Cleavelandite, muscovite, and lepidolite are also present.

Nova Bolinha, 200 meters to the north, has yielded some beryl and several perfect microcline crystals weighing up to 5 kilograms.

The Serra mine, in the municipality of Cachoeira west of Várzea Torta, has yielded about 1.5 tons of columbite. An analysis by the Campina Grande laboratory of the Departamento Nacional da Produção Mineral of an 800 kilogram sample gave 57.2 per cent Ni_2O_5 and 16.6 per cent Ta_2O_5. This is an unusually low tantalum and high niobium ratio for Northeastern Brazil. The mine also produced some amblygonite and beryl.

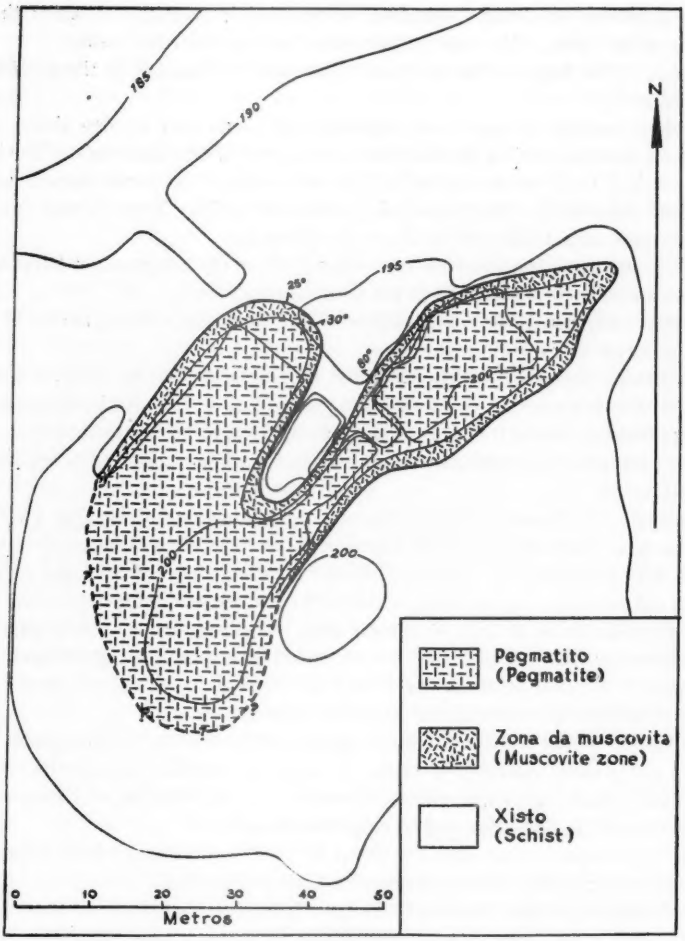

FIGURE 36.—*Sketch map of Várzea Torta, Cachoeira, Ceará*

Contour interval 5 meters. Assumed altitude

CASCAVEL-CRISTAIS AREA, CEARÁ

General considerations.—The area shown in Figure 4 includes parts of the municipalities of Guaraní, Cascavel, and Aracoiaba. It is a region of gently rolling topography with low relief. A few low rounded hills rise above the general level of the land. The country rock is mica schist, generally deeply weathered. Wind-blown sand covering the older rocks extends inland from the sea coast for 20 to 30 km.

The pegmatites generally are small and without topographic expression save for a covering of residual fragments of quartz. Weathering processes, in places, have reduced feldspars to kaolin.

The 11 mines here briefly described are believed to be characteristic of the pegmatites of this area. No maps of individual pegmatites were made.

Angicos.—The Angicos mine is about 15 km. east of Guaraní, in the municipality of Cascavel.

Residual boulders of quartz and pegmatite are found over an area about 100 by 40 meters, but the limits of the dike itself are exposed in two open cuts. The largest open cut is 4 by 4 meters and about 3½ meters deep. In it are exposed zones II and I and the contact with the enclosing muscovite schist. Zone I is well developed and contains mica books up to 15 cm. in diameter.

This pegmatite is reported to have yielded about 30 kilograms of beryl and 40 kilos of tantalite, principally from the residual alluvium.

Bangue.—Bangue, in the municipality of Cascavel, is about 10 km. north of Cristais and 1 km. east of the main highway.

It is a small pegmatite, which, from poor exposures, appears to be about 30 meters long and 10 meters wide. It has a small quartz core surrounded by a narrow shell of large feldspar crystals. Most of the dike appears to belong to zone II.

This pegmatite has produced a small quantity of tantalite and beryl from the alluvial cover.

Joazeiro.—The Joazeiro mine, in the municipality of Guaraní, is about 4 km. north of Cristais, on the west side of the highway. It is worked by Alberto Sá.

The dike is marked by a residual blanket of fragments of quartz and pegmatite, but its contacts with the enclosing schist have been exposed in only two cuts. These show the dike to be at least 40 meters long. It has a strong central quartz core approximately 3 meters wide that is surrounded by a sheath of big feldspar crystals averaging 1 meter in width. Zone II is 1 to 3 meters in width, and zone I, which contains large books of muscovite, is 0.5 to 1 meter wide.

This mine is said to have produced about 6 tons of beryl, 200 kilograms of tantalite, and a small quantity of mica. It does not contain amblygonite.

Jatobá.—Jatobá is 14 km. west of Garaní in the municipality of Cascavel. It is in the fazenda Jatobá belonging to Augusto Araripe.

The mine consists of an open cut about 30 by 15 meters and 5 meters deep which exposes a poorly differentiated pegmatite enclosed in schist.

Production from this mine is said to have been 4 tons of beryl, 10 tons of amblygonite, and a few kilograms of tantalite.

Jucas No. 1.—Jucas No. 1 is in the municipality of Cascavel about 1 km. northeast of Cristais. The country rock is schist.

The dike is in a small rounded knoll protected by residual quartz fragments up to 50 cm. in diameter. An open cut at the center of the knoll about 10 by 3 meters in area and 3 meters deep exposes the intergrowth of quartz, mica, and feldspar characteristic of zone II. A little bladed biotite is also present. Zone III appears to be absent, and zone IV is represented by a small pocket of milky quartz. The amount of residual quartz, however, indicates that most of zone IV has been eroded.

This pegmatite has yielded a small amount of beryl and tantalite.

Jucas No. 2.—Jucas No. 2, in the municipality of Cascavel, is about 3 km. northeast of Cristais.

This dike has a strong quartz core about 20 by 3 meters in area, surrounded by 1 to 2 meters of coarse feldspar. Most of the outcrop area of the dike is zone III. Zone I is narrow. A few hornblende crystals were observed in zone II.

This pegmatite has yielded small quantities of beryl and tantalite but no amblygonite.

Lago do Brito.—Lago do Brito is in the municipality of Cascavel about 24 km. southeast of Guaraní on the fazenda of João Batista dos Santos.

This was the site of the original discovery of amblygonite in Ceará (Leonardos, 1942).

Since late 1941, the mine is said to have produced about 200 tons of amblygonite.

In early October 1944 the mine pit, about 40 by 20 meters, was filled with water, and no pegmatite in place was visible. The dump contained quartz, albitized microcline, normal pegmatite, and some lepidolite. In addition to the amblygonite, the mine is said to have yielded about tons of beryl and a small amount of tantalite.

Mulungú.—Mulungú, in the municipality of Aracoiaba, is about 4 km. west of Cristais, in early October 1944 this mine was filled with water, and no pegmatite in place was visible. The following description is taken from a report by Armstrong, who visited the property in early June 1943.

"The original outcrop of the pegmatite was only 50 cm. wide but in depth it widened to 5 meters. The strike of the dike is N40°W cutting across the foliation of the enclosing schist which strike S30°W. The yield during its 6 months of operation was about 83 tons of beryl, 58 tons of amblygonite, and about 250 kilos of tantalite".

The dump contains mixed pegmatite, quartz, and much cleavelandite; some of the cleavelandite contains many bright-red garnet crystals, probably grossularite, less than 5 mm. in diameter. This association of cleavelandite and grossularite is similar to that at the Poço dos Cavalos mine, near Cachoeira. The dump also contained many soft green micaceous aggregates which appear to be a sericitic replacement of albite.

Parelhas.—The Parelhas mines, in the municipality of Aracoiaba, is about 2.5 km. northwest of Cristais. In early October 1944 it was just being opened by the firm of Cortez, O'Grady & Cia. Ltda.

Pits over an area about 150 by 50 meters expose a flat-lying pegmatite composed principally of zones II and III. Zone I is narrow (0.3 m.), and zone IV has not been encountered. The feldspar is albitized microcline.

Work began here in July 1944, and the dike is not yet well exposed. It is reported to have produced about 6 tons of beryl, 3 tons of amblygonite, and about 200 kilograms of tantalite.

Serrinha No. 1.—Serrinha No. 1, in the municipality of Cascavel, is about 13 km. northeast of Cristais.

This is a roughly circular pegmatite about 40 meters in diameter. Originally it was worked for the mica in zone I, which is marked by a series of pits around the edge of the dike. Zone II makes up most of the pegmatite. Zone III is about 15 meters in diameter, and zone IV is represented by a few scattered pockets of quartz.

The muscovite in zone I occurs in books up to 20 cm. in diameter. Most of it, however, is undulating and stained. About 2 tons of crude mica were in stock at

the mine. This pegmatite is reported to have also produced about 5 tons of beryl and a little tantalite.

Serrinha No. 2.—This mine is about 500 meters south of Serrinha No. 1. Work had just begun on a small pegmatite. An open cut has exposed about 4 square meters of the feldspars of zone III.

Alluvial beryl had been found here, but no tantalite or amblygonite.

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EUSTATIC SHORE LINES IN THE PACIFIC

BY HAROLD T. STEARNS

CONTENTS

	Page
Abstract	1071
Terraces on Espiritu Santo Island, New Hebrides group	1072
Terrace at 560 feet	1072
Terraces between 150 and 560 feet	1072
Submarine shelf at minus 300± feet	1072
Terrace at 100 feet	1072
Shore line at 45 feet	1073
Submarine shelf at minus 60± feet	1073
Shore line at 27 feet	1073
Shore line at 5 feet	1073
Terraces higher than 560 feet	1074
Age of the limestones	1074
Comparison with terraces elsewhere	1074
Terraces on Saipan Island, Marianas group	1074
Terraces on Guadalcanal Island, Solomon group	1075
Eustatic movements	1076
Conclusions	1076
References cited	1077

ILLUSTRATIONS

Plate	Facing page
1. Coralliferous limestones, Espiritu Santo Island	1072
2. Marine terraces, Saipan and Guadalcanal islands	1073

ABSTRACT

A suite of shore lines and horizontal coralliferous limestone terraces of Quaternary age, indicating halts of the sea 560, 260, 215, 150, 100, 45, 27, and 5 feet above mean sea level, and drowned valleys and shelves indicating halts at about 60 and 300 feet below sea level are present on Espiritu Santo Island in the New Hebrides group. Other terraces at intermediate levels above 45 feet were seen, but their altitudes were not determined. Remnants of a terrace about 1200 feet above sea level are also present. The terraces correspond in altitude and in sequence with those on the Hawaiian Islands about 3000 miles away, which seems to indicate that eustatic shifts in sea level ranging from at least 300 feet below to 560 feet above present sea level may have occurred in Quaternary time. Several of the terraces have been identified on Saipan in the Marianas Islands 3200 miles west of the Hawaiian Islands and 2229 miles north of Espiritu Santo Island. Four hypotheses are offered to account for the great shifts in sea level. It is believed that these eustatic shifts gave opportunity for the great development of coral reefs in the Pacific in Pleistocene time. The smaller

shifts appear to be chiefly the result of the rise and fall of sea level concomitant with glaciation and deglaciation and concurrent changes in the configuration of the ocean floors.

TERRACES ON ESPIRITU SANTO ISLAND, NEW HEBRIDES GROUP

TERRACE AT 560 FEET

The most extensive terrace on the island covers many square miles and is composed of coralliferous limestone. A dumpy-level line[1] indicates that it is 560 feet above mean sea level at its inland edge. The rock in the terrace is porous, well-cemented, typical fossiliferous reef and reef detritus. Horizontal bedding is common. The limestone contains corals in position of growth and many mollusks, including a giant clam, in a matrix of sand, shell fragments, and foraminifers. Excellent exposures indicate that the riser of the terrace consists of this limestone, but its tread consists of a thin veneer of limestone over older rocks, chiefly faulted marls, shales, and detrital limestone. The terrace extends untilted for 30 miles along the eastern part of the island and undulates between 520 and 550 feet depending upon the extent of gullying and weathering. It carries usually 6 to 8 feet of soil commonly burying pinnacled limestone (*Karrenfeld*).

TERRACES BETWEEN 150 AND 560 FEET

A narrow terrace at 480 feet near the mouth of the Renée River may indicate a short halt at that level, but the river gravel on it may mean that it is stream-cut. Remnants of a terrace about 375 feet above sea level were noted in a few places. A broad terrace exists, the inner edge of which was not reached. It rises from 290 to 340 feet (barometer) in a distance of 4 miles. It may be the sloping tread of the 375-foot terrace. Narrow terraces at 300 feet (barometer) were also noted. A terrace at slightly more than 260 feet by dumpy-level line and usually less than a mile wide is a prominent feature of the landscape. The limestone in a quarry at an altitude of 225 feet is horizontally bedded coralliferous limestone (Pl. 1, fig. 1). The terrace appears in places to be largely wave cut into the older limestone. A narrow poorly preserved terrace 215 feet high (barometer) is notched into the 260-foot terrace, and below it is another at 150 feet (barometer). The latter terrace is well developed east of the Sarakata River.

SUBMARINE SHELF AT MINUS 300± FEET

Segond Channel separating Aore Island from Espiritu Santo resulted from partial drowning of the canyons of the Sarakata and Renée rivers. Soundings indicate that the canyons are drowned about 300 feet, but coral debris and delta deposits have partly filled it in places.

TERRACE AT 100 FEET

A terrace with its inland edge determined by dumpy-level line as 100 feet above mean sea level is prominent in many places along the southern and western shores

[1]All level lines on Espiritu Santo Island were run by a Naval Construction Regiment.

FIGURE 1. BEDDED CORALLIFEROUS LIMESTONE 225 FEET ABOVE SEA LEVEL
Photo by H. T. Stearns.

FIGURE 2. CORAL PIT IN DEPOSITS OF THE 27-FOOT STAND OF THE SEA.
Photo by U. S. Navy.

CORALLIFEROUS LIMESTONES, ESPIRITU SANTO ISLAND

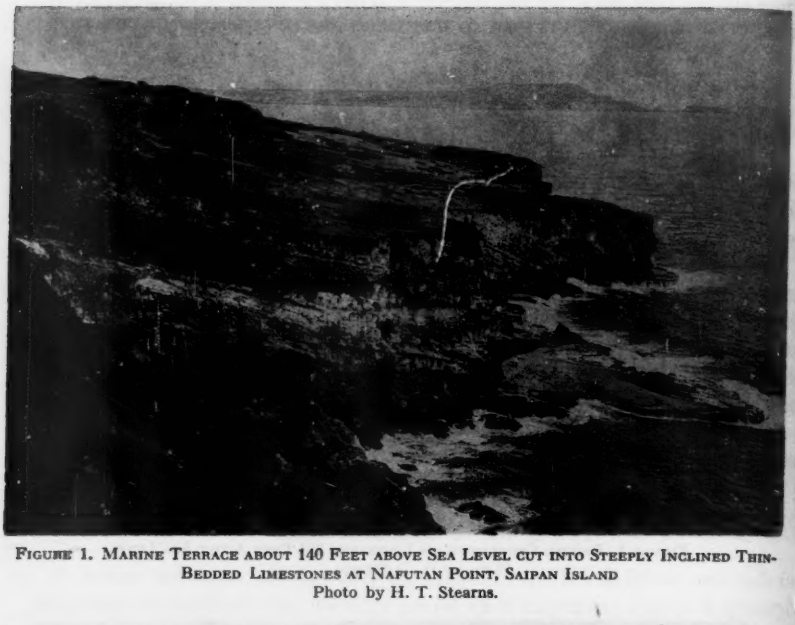

FIGURE 1. MARINE TERRACE ABOUT 140 FEET ABOVE SEA LEVEL CUT INTO STEEPLY INCLINED THIN-BEDDED LIMESTONES AT NAFUTAN POINT, SAIPAN ISLAND
Photo by H. T. Stearns.

FIGURE 2. MARINE TERRACES CUT IN WEAK MARLS AND SHALES, GUADALCANAL ISLAND
Courtesy of Life Magazine.

MARINE TERRACES, SAIPAN AND GUADALCANAL ISLANDS

of the island. It is much narrower than the 260-foot terrace. A few offshore islets of limestone are the same height, but it was not established whether they are reef that grew during this stand of the sea or beveled older limestone. The floor of a sea cave on near-by Aore Island is 95 feet above mean sea level.

SHORE LINE AT 45 FEET

A very narrow terrace of limestone indicates a short halt at 45 feet above mean sea level. It was cut by waves in the limestone of the 100-foot terrace. A typical wave-cut notch several feet deep and several hundred feet long made in older limestone lies just inland of the shore road, a quarter of a mile east of the Sarakata River. A dumpy-level line to the apex of the notch indicates that it is at an elevation of 48 feet above mean low water which is approximately 2.9 feet below mean sea level. It faces a channel free from storm waves, hence gives a precise altitude for this stand of the sea. Although traces of this shore line have been found in the Hawaiian Islands, this is the first locality the writer has found in the Pacific where its precise altitude could be determined. Consolidated beach deposits of this stand of the sea lie near a large Navy well at the southeast corner of Espiritu Santo Island. The loose calcareous deposits of the 27-foot stand of the sea are unconformable on the lower slopes of these beach deposits.

SUBMARINE SHELF AT MINUS 60± FEET

Soundings along the south coast indicate a narrow submarine shelf at 10 to 12 fathoms. The bottom drops abruptly from this depth to 30 to 50 fathoms. In some places, addition of coral and detritus have decreased to 8 fathoms the depth of the shelf. The shelf appears to indicate a submerged shore line between 60 and 70 feet below sea level.

SHORE LINE AT 27 FEET

The most prominent low terrace is a bench several yards to half a mile across and about 25 feet above sea level. Levels were run to several excellent deposits of beach rock laid down by this sea. Their tops average 30 feet above mean sea level. The tops of beaches of the present sea are about 3 feet above mean sea level which places the emerged shore line at 27 feet. The detritus left by this sea is exposed in many excavations lying unconformably upon the older limestones. It is much less consolidated than the older limestones and can be removed by steam shovel without blasting (Pl. 1, fig. 2). It consists of fragments of water-worn mollusks, coral and coral sand, a few large upright fossil coral heads several feet across, and giant clam shells. About 8 miles up the Sarakata River, rapids are formed by beach conglomerates of this stand of the sea. Numerous large caverns exist in the older limestones where waves of the 27-foot sea beat against them.

SHORE LINE AT 5 FEET

Remnants of coral reef 5 feet above sea level are common along some stretches of the shore. They are seldom more than 10 yards wide and are notched at their

base by the present sea. They consist chiefly of upright coral heads bound together by coralline algae. The present fringing reef is, in places, the beveled 5-foot reef with little or no reef growth of the present sea except at the outer edge. Numerous abandoned caves and notches indicate the 5-foot shore line. The small amount of reef development during this stand indicates the halt lasted a much shorter time than the 27-foot stand.

TERRACES HIGHER THAN 560 FEET

Mawson (1905, p. 421) reports emerged reef limestone 1000 feet above sea level lying on marine tuffs. The writer saw mesas of this limestone from the air but did not determine their altitude from the ground. An estimate of the height of the mesas by comparison with the 560-foot terrace directly beneath them confirms Mawson's report that the highest emerged limestone is at least 1000 feet above sea level. U. S. Hydrographic Chart 2883 shows one at 1200 feet. The level tops of the mesas indicate that they are later than the underlying warped tuffs and marls. Although more precise data are needed to establish the shore line correlative with the high coralliferous limestone, the island was submerged relatively late in its geologic history to a depth of about 1200 feet.

Small remnants of a terrace at an altitude of about 650 feet lie between the upper terrace and the extensive one at an altitude of 560 feet. Other narrow terraces lie between 650 and 1200 feet, but their altitudes were not determined.

AGE OF THE LIMESTONES

Fossil corals and mollusks collected from the limestones from 560 feet to the lowest level have been sent to the National Museum for identification but because of the war have not been studied. It is believed that they are Pleistocene in age from their similarity to others from the Pacific. However, the age of fossils in Pacific Islands is still in a controversial stage; hence, the 560-foot and higher terraces might be late Pliocene instead of earliest Pleistocene. None of the limestones are deformed; hence, they stand in sharp contrast to the underlying older folded Tertiary marls and marine tuffs.

COMPARISON WITH TERRACES ELSEWHERE

Table 1 compares the terraces on Espiritu Santo Island with those on the Hawaiian Islands (Stearns, 1935, p. 1927–1956; 1938, p. 615–628) 3000 miles to the northeast and with those on the Atlantic coast of the United States (Parker and Cooke, 1944, p. 22). They are listed according to age with the oldest at the bottom.

TERRACES ON SAIPAN ISLAND, MARIANAS GROUP

Prominent terraces cut into Tertiary limestone, and older rocks skirt the shores of Saipan Island. The most recent is 5 feet above present sea level. In places, especially at Agingan Point, deep notches are cut into the limestones at this level. Patches of emerged reef that grew during this period are common. The next higher is 25 feet above sea level. Narrow patches of reef that grew in this sea exist inland of Charon Kanoa. Along the southern shore of Saipan at an altitude of 45 feet by dumpy-level line, a prominent terrace, in places a quarter of a mile across, is cut

into older limestone and terminates in an abandoned sea cliff full of caves. The inland edge of the next higher terrace is 70 feet above sea level at the base of an abandoned sea cliff. Near Obiam Point a notch 100 feet above sea level (barometer) is preserved in this cliff. The 100-foot terrace is extensive in many places, indicating that sufficient time elapsed for coral reefs to form during this halt. The next higher terrace terminates 140 feet (barometer) above mean sea level at the base of a wave-cut cliff. At Nafutan Point, the 140-foot terrace is cut into steeply inclined thin-bedded limestones (Pl. 2, fig. 1); hence, its wave-erosional origin is clear.

TABLE 1.—*Altitudes of Quaternary shore lines on Espiritu Santo Island, the Hawaiian Islands, and the Atlantic coast of the United States*

Espiritu Santo Island	Hawaiian Islands	U. S. Atlantic coast
feet	*feet*	*feet*
0	0	0
+5	+5	+5
+27	+25*	+25
−60±	−60±	Low
+45	+40±	+42
Not found	+70	+70
+100	+100	+100
−300±	−300±	Low
+150	—	+170
+215	—	+215
+260+	+250±	+270
Trace	+325±	
Do	+375±	
+560	+560	
Trace (?)	+625±	
+1200±	+1200±	
Not found	−1200±	

*Consists of two shore lines, one 22 feet and the other 27 feet above mean sea level.

The most extensive terrace is at an altitude of 260 feet. It cuts across Tertiary limestones, shales, and volcanics for several miles along the eastern coast. Near Donnay Village the terrace is composed of reef limestone that accumulated during the 260-foot halt. The limestone is more than 200 feet thick near the shore but becomes a thin veneer at the inland edge of the terrace. It lies unconformably on the older rocks in numerous exposures along the main road.

Several higher terraces were found, but terraces caused by fault blocks of resistant Tertiary limestone are so numerous that the higher marine Pleistocene terraces could not be distinguished with certainty. The valleys on the island are too small to indicate drowning; hence, evidence of low stands of the sea were not found.

TERRACES ON GUADALCANAL ISLAND, SOLOMON GROUP

Guadalcanal in the Solomon group shows a well-preserved suite of horizontal terraces (Pl. 2, fig. 2), the most prominent being at 260 feet (barometer) and about 560 feet above sea level. The 5- and 25-foot terraces are narrow but definite features

between Henderson Field and Kokumbona. A terrace about 150 feet above sea level borders this stretch of shore also. The coralliferous limestones on this island are thin and lie unconformably upon warped and faulted shales and marls. Near Kokumbona the limestone forms a cavernous cliff 150 feet high, but it is only a thin facing on a bluff of Tertiary marl. The limestones reach a height of about 1200 feet above mean sea level at Mt. Austin.

EUSTATIC MOVEMENTS

The shore lines below 260 feet in the islands described are undoubtedly eustatic as shown by comparison with those on the Atlantic coast and in Hawaii. They seem to have been formed during the fluctuating seas corresponding to the Pleistocene glaciations and deglaciations and the concurrent changes in the configuration of the ocean basins. The 560-foot shore line likewise appears to be eustatic as it occurs on both Espiritu Santo Island and the Hawaiian Islands. Admittedly, its similar height could be a coincidence, and the final decision regarding its origin must await study of high shore lines on other islands in the Pacific. Efate and Malekula islands in the New Hebrides group carry well-defined flights of horizontal terraces. Accurate level work on these islands will add valuable knowledge to the problem of high eustatic shore lines in the Pacific.

The horizontality of emerged reefs in the Loyalty group so impressed Suess (1900, p. 532–534) that he long ago interpreted them as having emerged as a result of recession of sea level of about 330 feet. The writer has flown over all the islands from New Caledonia to Guadalcanal and has seen horizontal limestone terraces extending for miles on the islands in this area. A check of the literature about islands in the Pacific leads to the conclusion that few, if any, Quaternary coralliferous limestones in Oceania are tilted. Davis (1928) reports tilted emerged atolls, but he describes topographic surfaces and not deformed bedding. Many of them in Fiji have been shown to be Tertiary foraminiferal limestones and not emerged atolls (Ladd and Hoffmeister, 1945, p. 167–174).

An emerged barrier reef extending from present sea level to an altitude of about 375 feet on Montagnes Peninsula, 9 miles south of Tantouta, New Caledonia, was found by the writer in 1943. This reef is undisturbed in spite of the great amount of tertiary faulting and folding of the island. Fossils have not been collected from this reef, but its lack of deformation points to Pleistocene age. The suite of terraces cut in the side of the thick emerged near-atoll making up the northern part of Guam shows no tilting. Rota, Aguijan, and Tinian islands have similar horizontal terraces.

The high terraces on some coasts such as along New Zealand and California are tilted, but the movement was local.

CONCLUSIONS

The analogy of altitude and sequence between the Quaternary shore lines on Espiritu Santo Island and those on the Hawaiian Islands suggests eustatic movements of sea level ranging from at least 300 feet below to 560 feet above present sea level. Some evidence exists that the range may have been from 1200 feet or more

below to about 1200 feet above present sea level. Such large shifts, if they occurred, would have affected the accumulation and melting of the Pleistocene glaciers.

Eustatic movements between 560 feet above and 300 feet below present sea level are much greater than the accepted vertical movement of the sea calculated for the subtraction and addition of water for the growth and melting of the Pleistocene ice caps. It appears that such large eustatic shifts must have some other cause.

One or more of the following would account for the great changes in ocean level:

(1) Changes in the configuration of ocean basins especially in areas where emerged shore lines are tilted.

(2) Volume changes within the earth's crust causing the entire crust to expand and contract.

(3) Outpouring of sufficient lava on the ocean floor to cause a great rise in sea level subsequently compensated for by sinking of the floor there or elsewhere.

(4) Continental drift.

Some of the smaller shifts resulted from changes in the volume of water stored in the Pleistocene ice caps, but the total change in level is too great to have resulted from glaciation and deglaciation. It is believed that these eustatic shifts of sea level in Quaternary time gave opportunity for the widespread development of coral reefs, many of which are now either above or below present sea level.

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